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Chuang et al.

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(54) **193NM LASER AND INSPECTION SYSTEM**

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This patent is subject to a terminal disclaimer.

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(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
H01S 3/30 (2006.01)
H01S 3/108 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H01S 3/1083*** (2013.01); ***G01N 21/84*** (2013.01); ***G01N 21/9501*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H01S 3/0092; H01S 3/0078; H01S 3/067; H01S 3/0602
USPC 372/5, 6, 21, 22, 41
See application file for complete search history.

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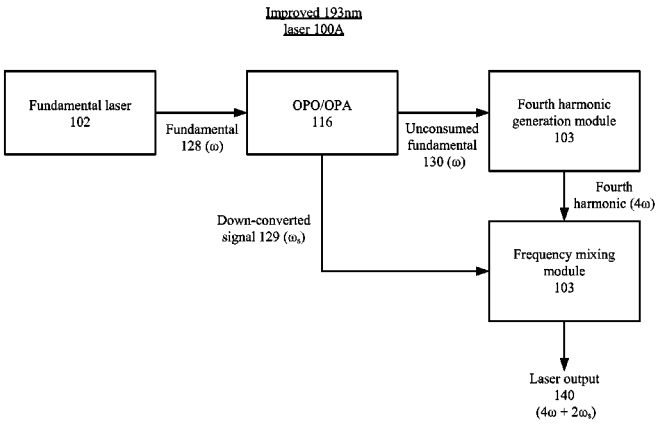
Primary Examiner — Kinam Park
(74) *Attorney, Agent, or Firm* — Bever, Hoffman & Harms, LLP

(57) **ABSTRACT**

A laser for generating an output wavelength of approximately 193.4 nm includes a fundamental laser, an optical parametric generator, a fourth harmonic generator, and a frequency mixing module. The optical parametric generator, which is coupled to the fundamental laser, can generate a down-converted signal. The fourth harmonic generator, which may be coupled to the optical parametric generator or the fundamental laser, can generate a fourth harmonic. The frequency mixing module, which is coupled to the optical parametric generator and the fourth harmonic generator, can generate a laser output at a frequency equal to a sum of the fourth harmonic and twice a frequency of the down-converted signal.

20 Claims, 19 Drawing Sheets



(51) **Int. Cl.**

H01S 3/00	(2006.01)
H01S 3/067	(2006.01)
H01S 3/06	(2006.01)
G01N 21/95	(2006.01)
G01N 21/84	(2006.01)
G01N 21/956	(2006.01)

(52) **U.S. Cl.**

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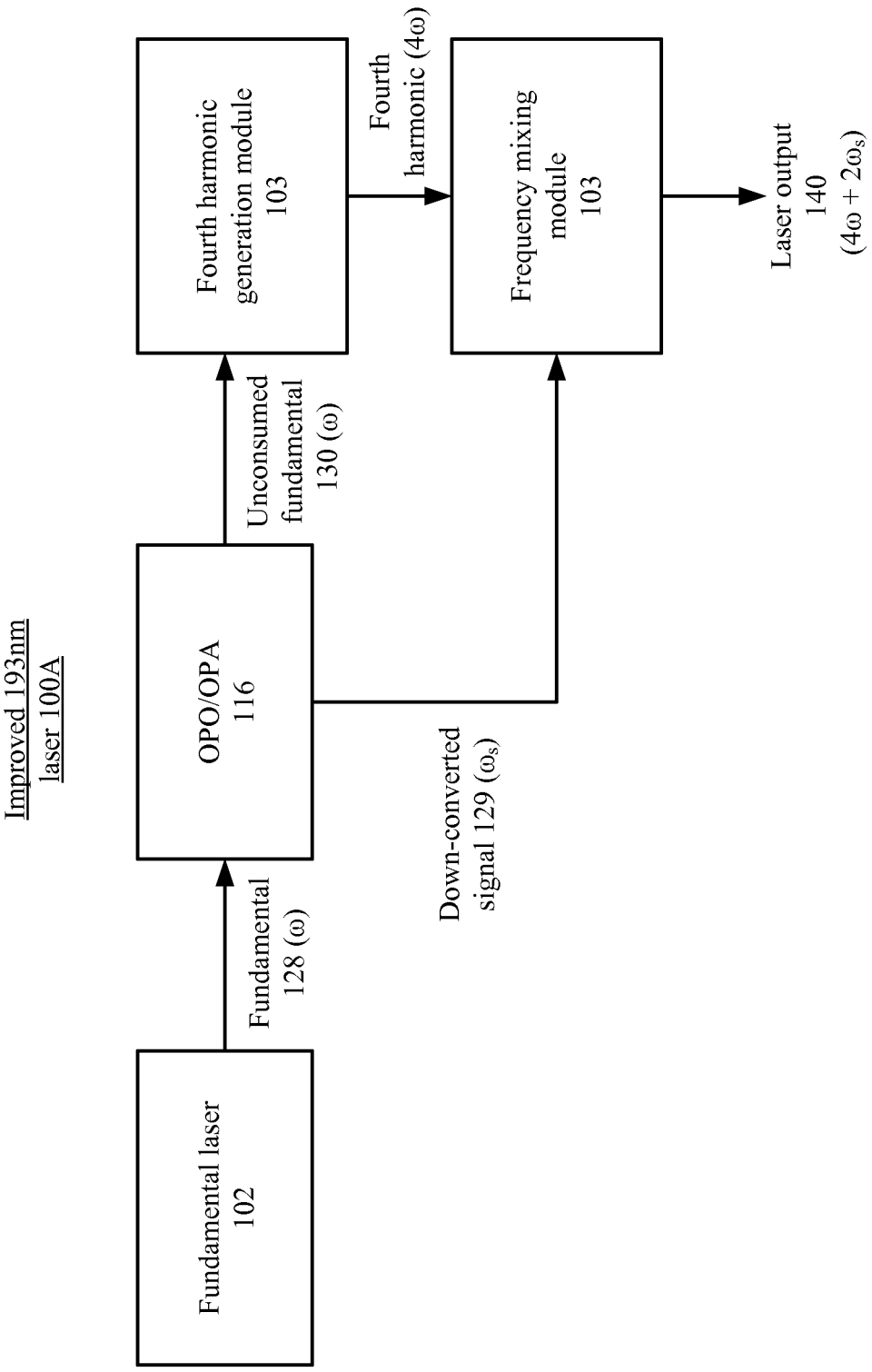

Improved 193nm laser 100A
Fundamental laser 102
Fundamental 128 (ω)
OPO/OPA 116
Unconsumed fundamental 130 (ω)
Down-converted signal 129 (ωs)
Fourth harmonic generation module 103
Fourth harmonic (4ω)
Frequency mixing module 103
Laser output 140 (4ω + 2ωs)

Figure 1A

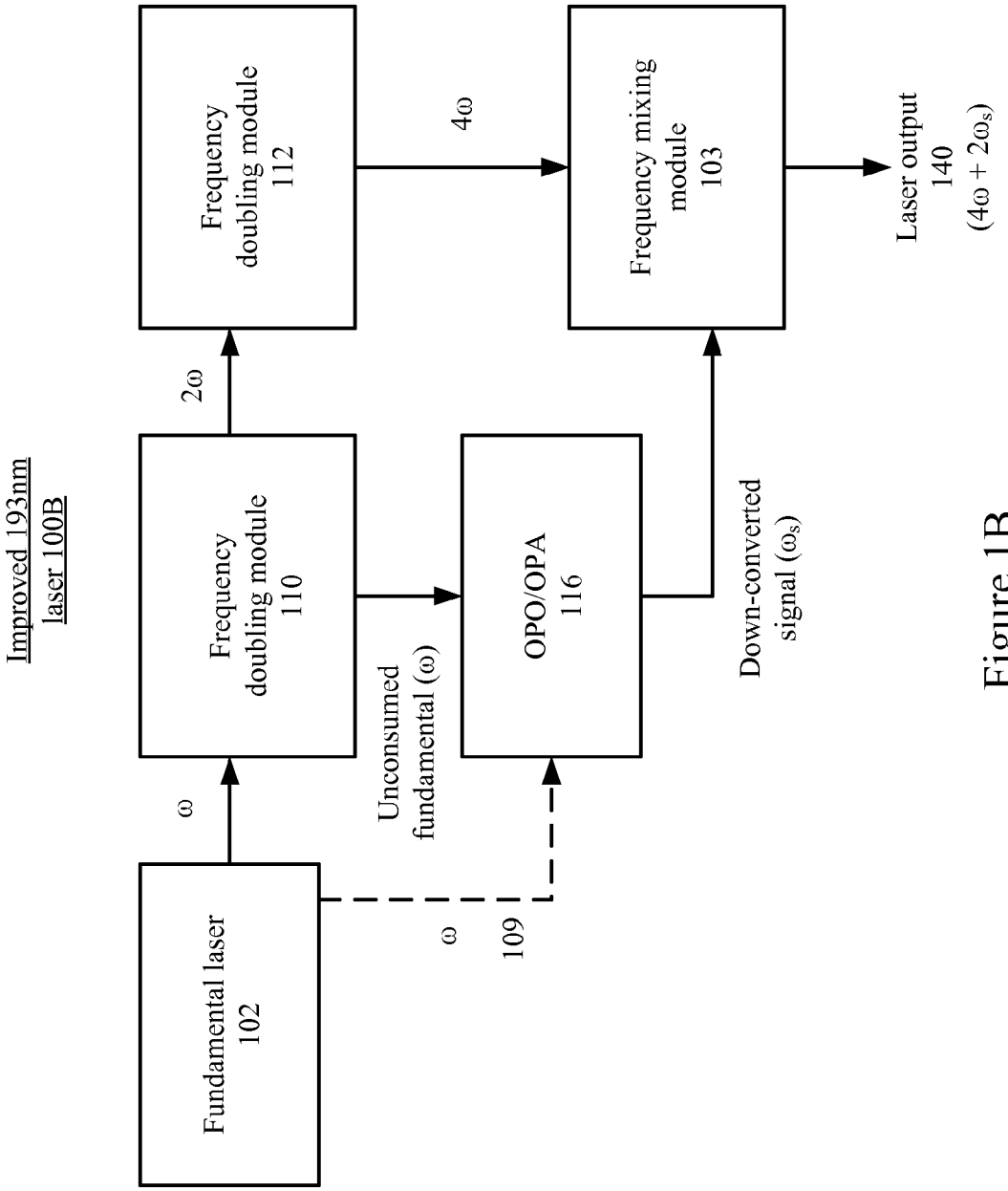

Improved 193nm laser 100B
Fundamental laser 102
ω
Frequency doubling module 110
2ω
Frequency doubling module 112
Unconsumed fundamental (ω)
ω
109
OPO/OPA 116
Down-converted signal (ω_s)
4ω
Frequency mixing module 103
Laser output 140
(4ω + 2ω_s)

Figure 1B

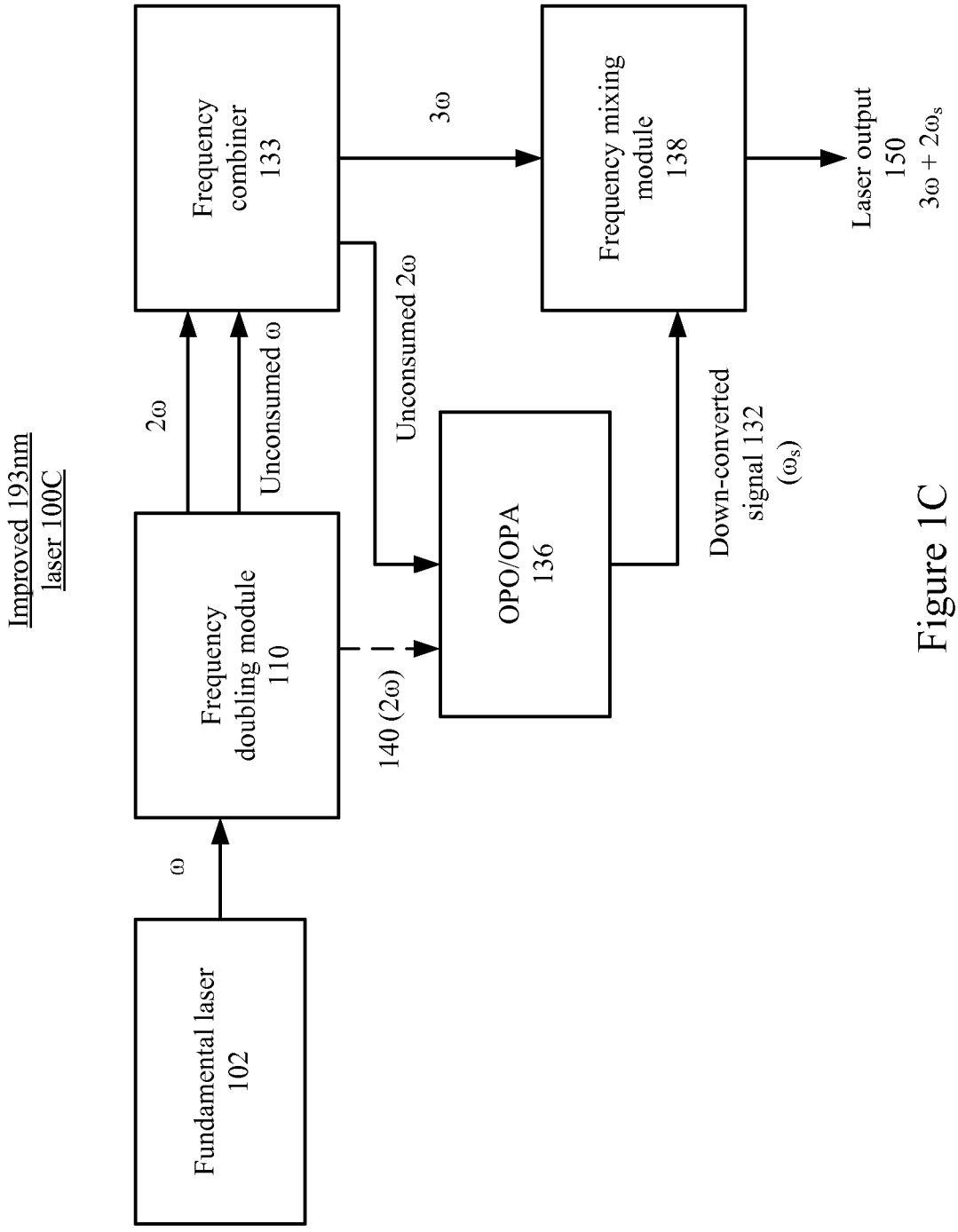

Improved 193nm laser 100C
Fundamental laser 102
ω
Frequency doubling module 110
2ω
Unconsumed ω
140 (2ω)
Unconsumed 2ω
Frequency combiner 133
3ω
OPO/OPA 136
Down-converted signal 132 (ω_s)
Frequency mixing module 138
Laser output 150
3ω + 2ω_s

Figure 1C

Figures 1A and 1B								
Fundamental laser type	Nd:Vandate, Nd:YAG, Yb-doped fiber		Nd:YLF		Nd:YLF		Yb-doped fiber	
Harmonic	Fundamental (short)	Fundamental (long)	Fundamental (short)	Fundamental (long)	Fundamental (short)	Fundamental (long)	Fundamental (short)	Fundamental (long)
ω	1064.0	1065.0	1052.0	1054.0	1046.0	1048.0	1029.0	1031.0
ω_s	1417.2	1413.7	1461.6	1453.9	1485.3	1477.3	1558.4	1549.3
2ω	532.0	532.5	526.0	527.0	523.0	524.0	514.5	515.5
4ω	266.0	266.3	263.0	263.5	261.5	262.0	257.3	257.8
$4\omega + \omega_s$	224.0	224.1	222.9	223.1	222.4	222.5	220.8	221.0
$4\omega + 2\omega_s$	193.4	193.4	193.4	193.4	193.4	193.4	193.4	193.4

Figure 1D

Figure 1C								
Fundamental laser type	Nd:Vandate, Nd:YAG, Yb-doped fiber		Nd:YLF		Nd:YLF		Yb-doped fiber	
Harmonic	Fundamental (short)	Fundamental (long)	Fundamental (short)	Fundamental (long)	Fundamental (short)	Fundamental (long)	Fundamental (short)	Fundamental (long)
ω	1064.0	1065.0	1052.0	1054.0	1046.0	1048.0	1029.0	1031.0
ω_s	850.7	849.7	862.5	860.5	868.6	866.5	886.8	884.6
2ω	532.0	532.5	526.0	527.0	523.0	524.0	514.5	515.5
3ω	354.7	355.0	350.7	351.3	348.7	349.3	343.0	343.7
$3\omega + \omega_s$	250.3	250.4	249.3	249.5	248.8	249.0	247.3	247.5
$3\omega + 2\omega_s$	193.4	193.4	193.4	193.4	193.4	193.4	193.4	193.4

Figure 1E

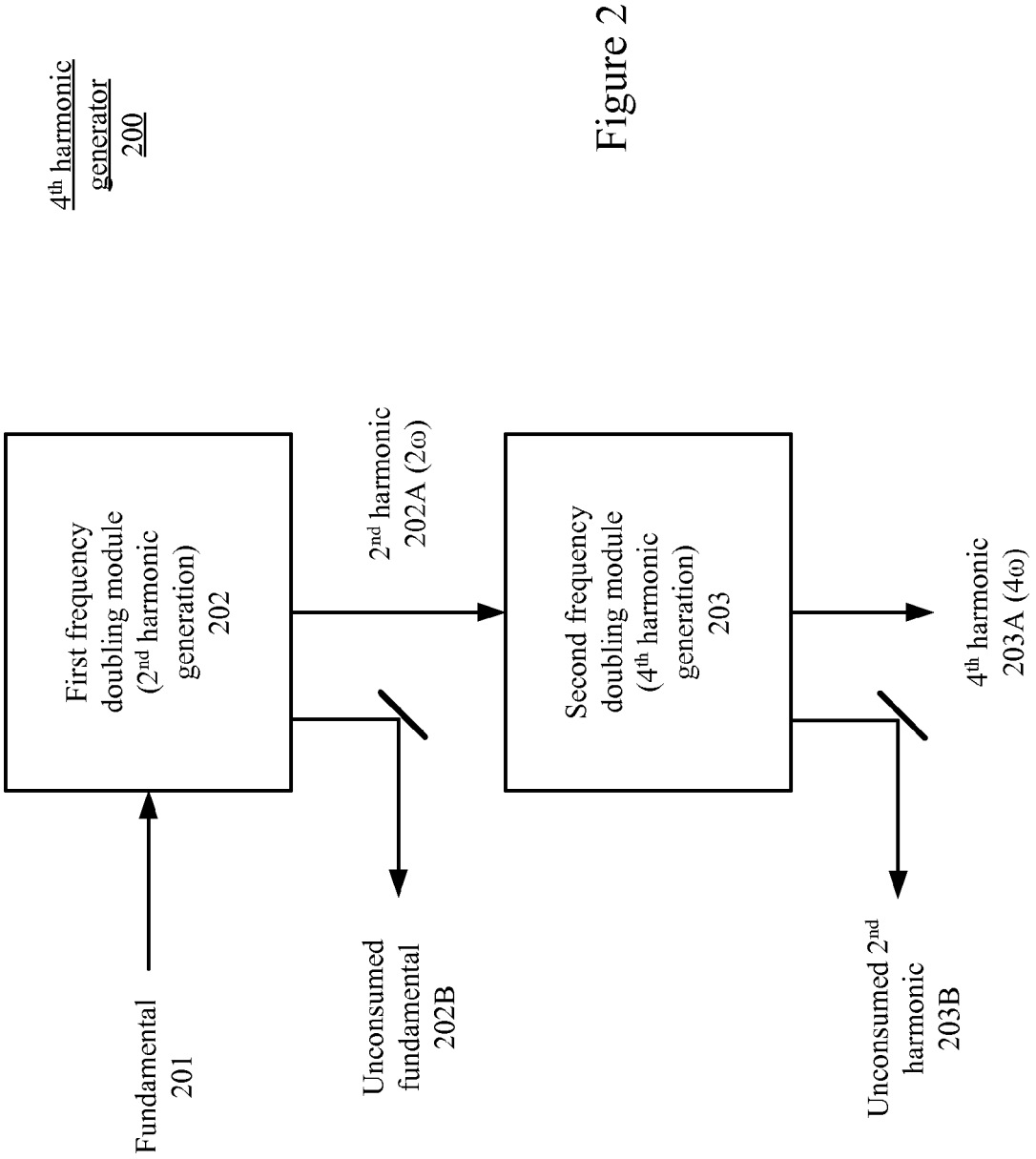

4th harmonic generator 200
First frequency doubling module (2nd harmonic generation) 202
2nd harmonic 202A (2ω)
Second frequency doubling module (4th harmonic generation) 203
4th harmonic 203A (4ω)
Fundamental 201
Unconsumed fundamental 202B
Unconsumed 2nd harmonic 203B

Figure 2

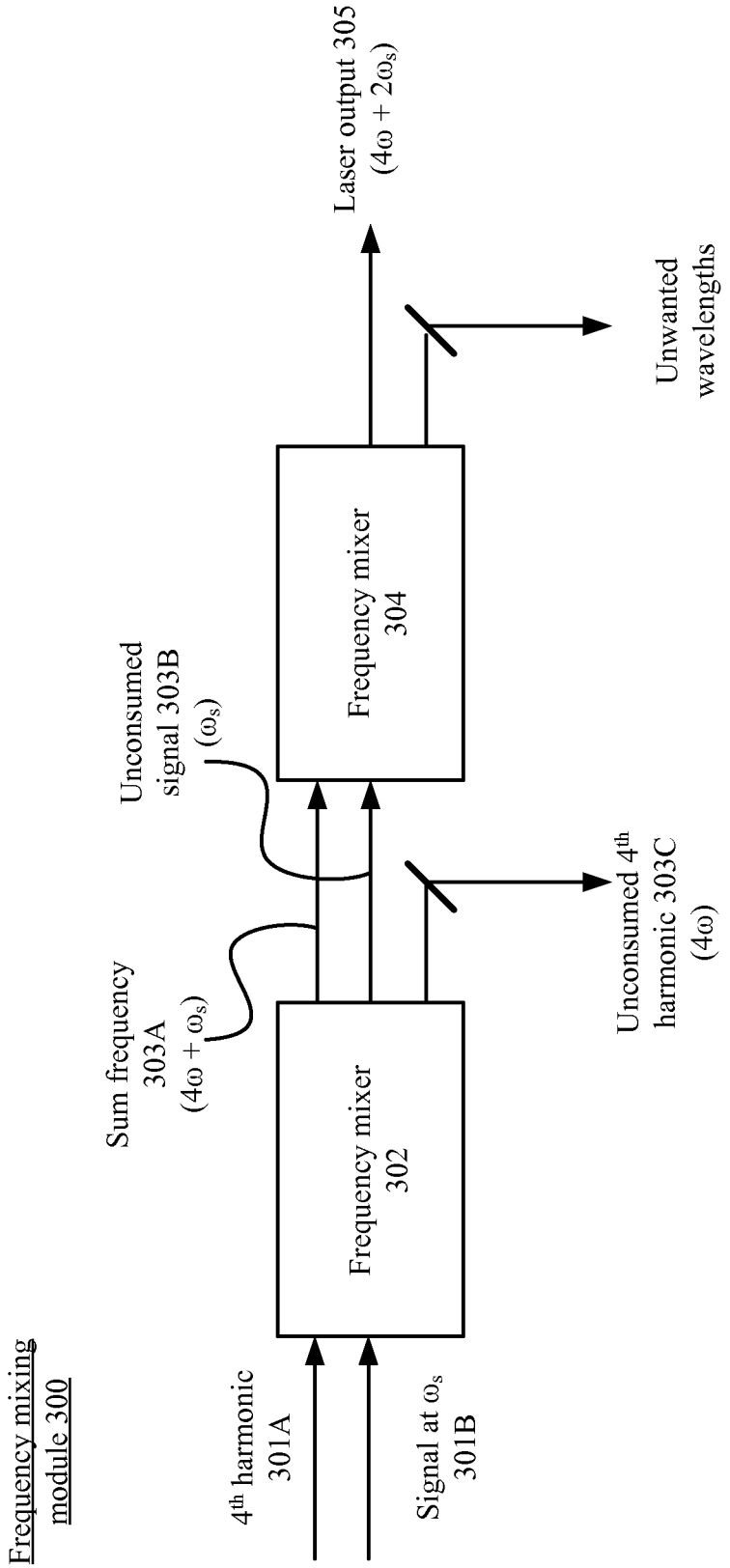

Frequency mixing module 300
4th harmonic 301A
Signal at ωs 301B
Frequency mixer 302
Sum frequency 303A (4ω + ωs)
Unconsumed signal 303B (ωs)
Unconsumed 4th harmonic 303C (4ω)
Frequency mixer 304
Laser output 305 (4ω + 2ωs)
Unwanted wavelengths

Figure 3

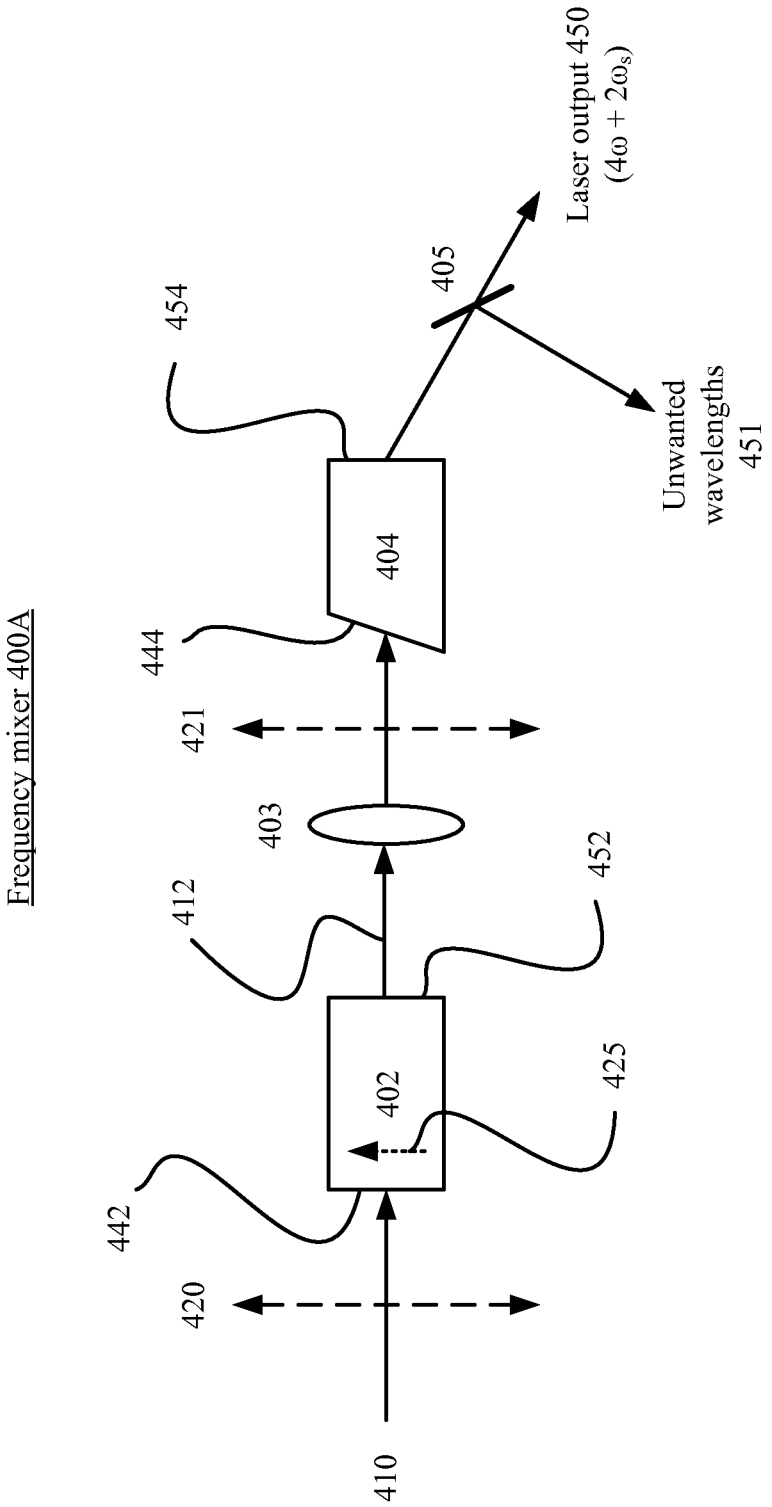

Frequency mixer 400A
Laser output 450
($4\omega + 2\omega_s$)
Unwanted
wavelengths
451
405
454
404
444
421
403
412
452
402
425
442
420
410

Figure 4A

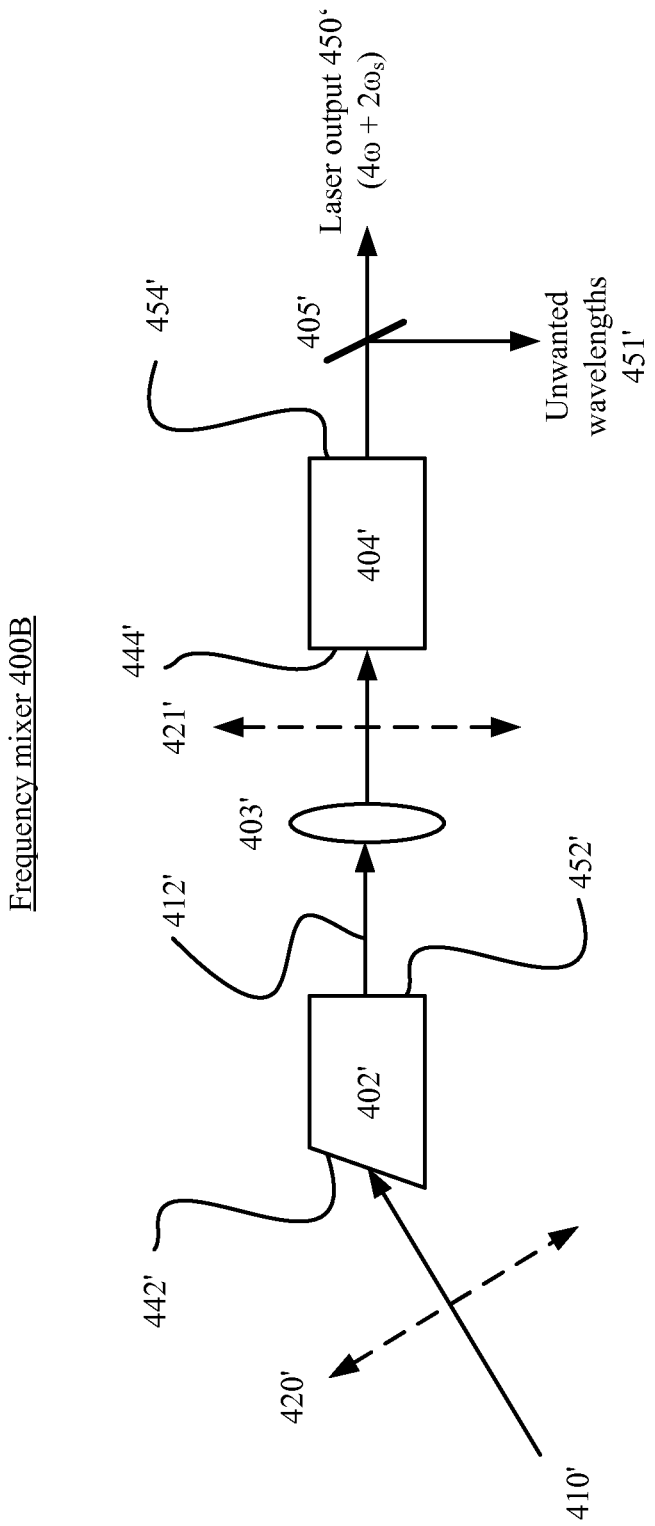

Frequency mixer 400B
Laser output 450'
($4\omega + 2\omega_s$)
Unwanted wavelengths 451'
405'
454'
404'
444'
421'
403'
412'
452'
402'
442'
420'
410'

Figure 4B

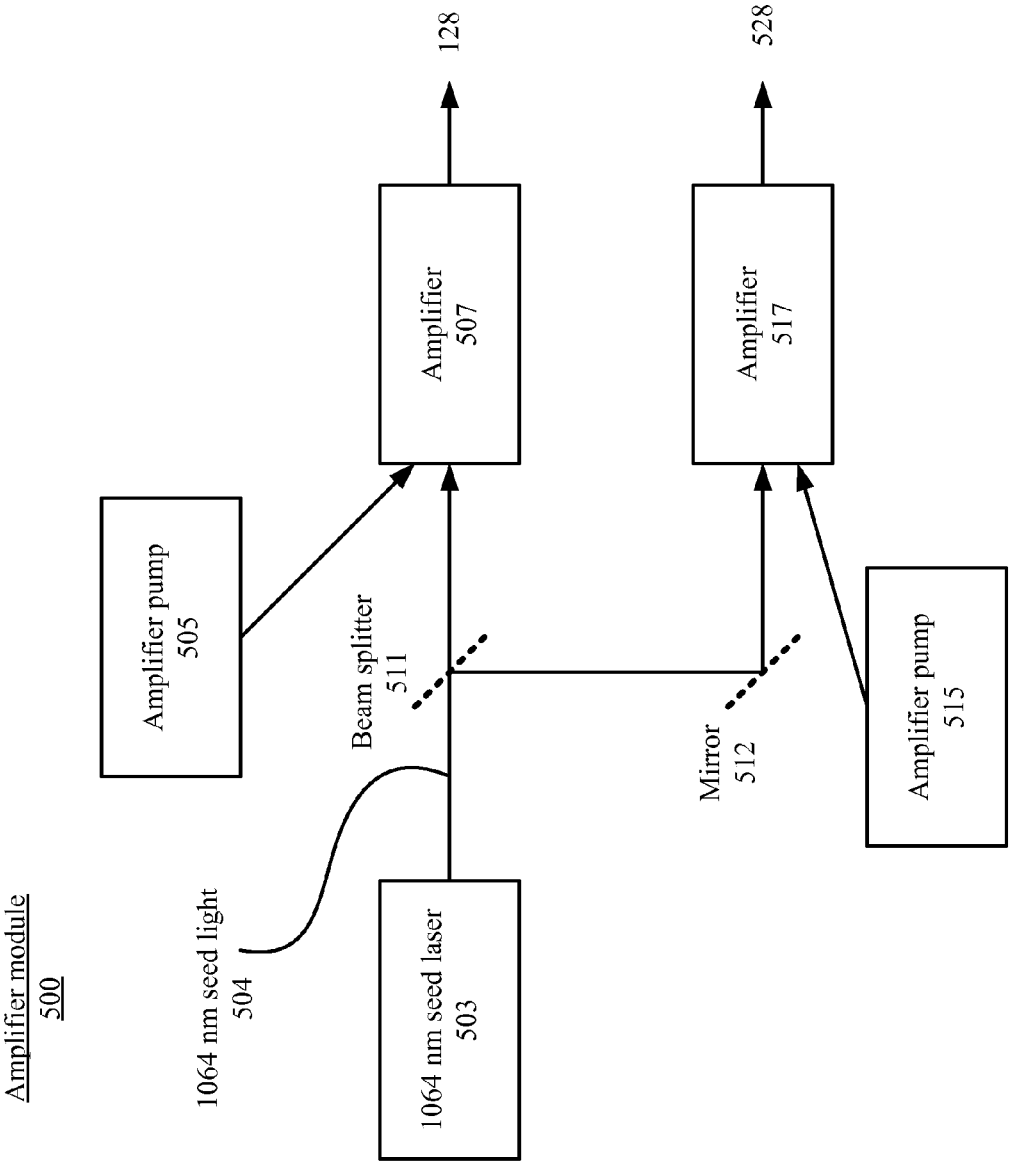

Amplifier module
500
1064 nm seed light
504
1064 nm seed laser
503
Amplifier pump
505
Beam splitter
511
Amplifier
507
128
Mirror
512
Amplifier
517
528
Amplifier pump
515

Figure 5

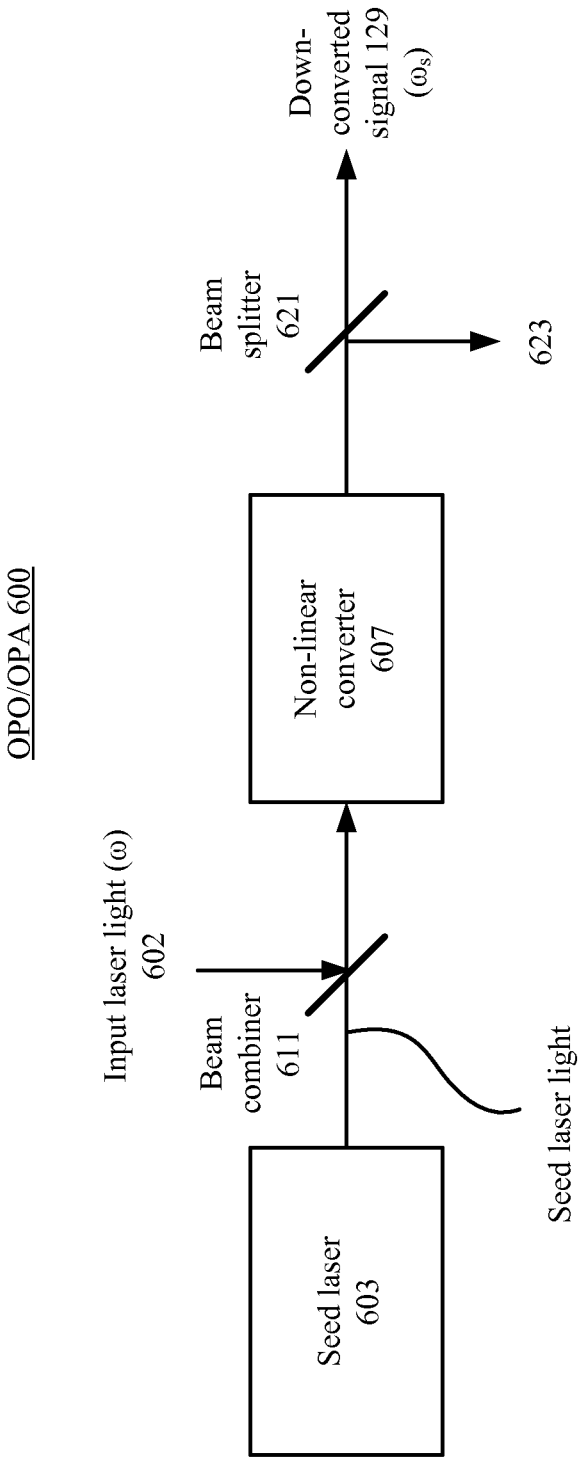

OPO/OPA 600
Input laser light (ω)
602
Beam
combiner
611
Seed laser
603
Seed laser light
604
Non-linear
converter
607
Beam
splitter
621
623
Down-
converted
signal 129
(ω_s)

Figure 6

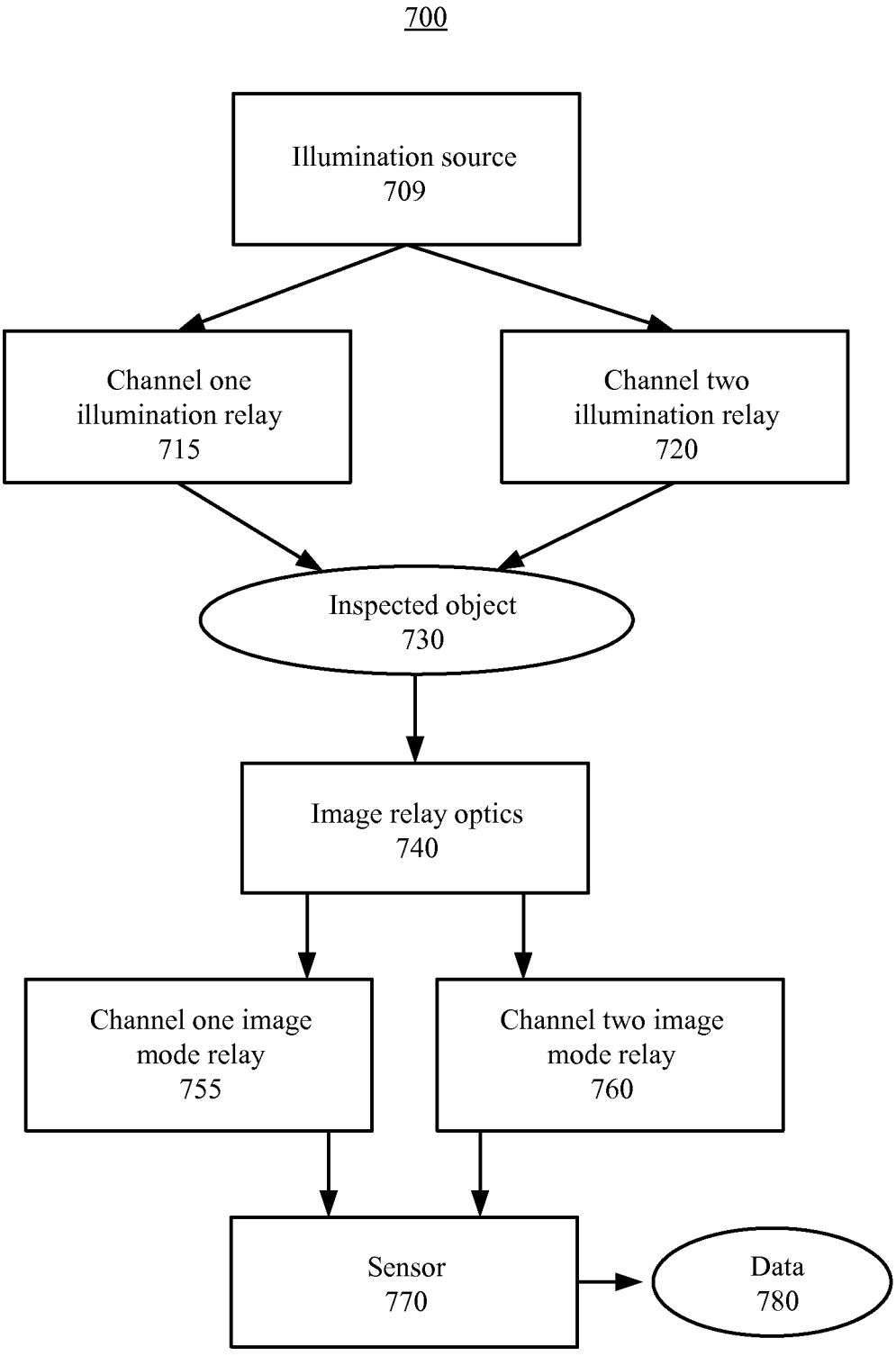
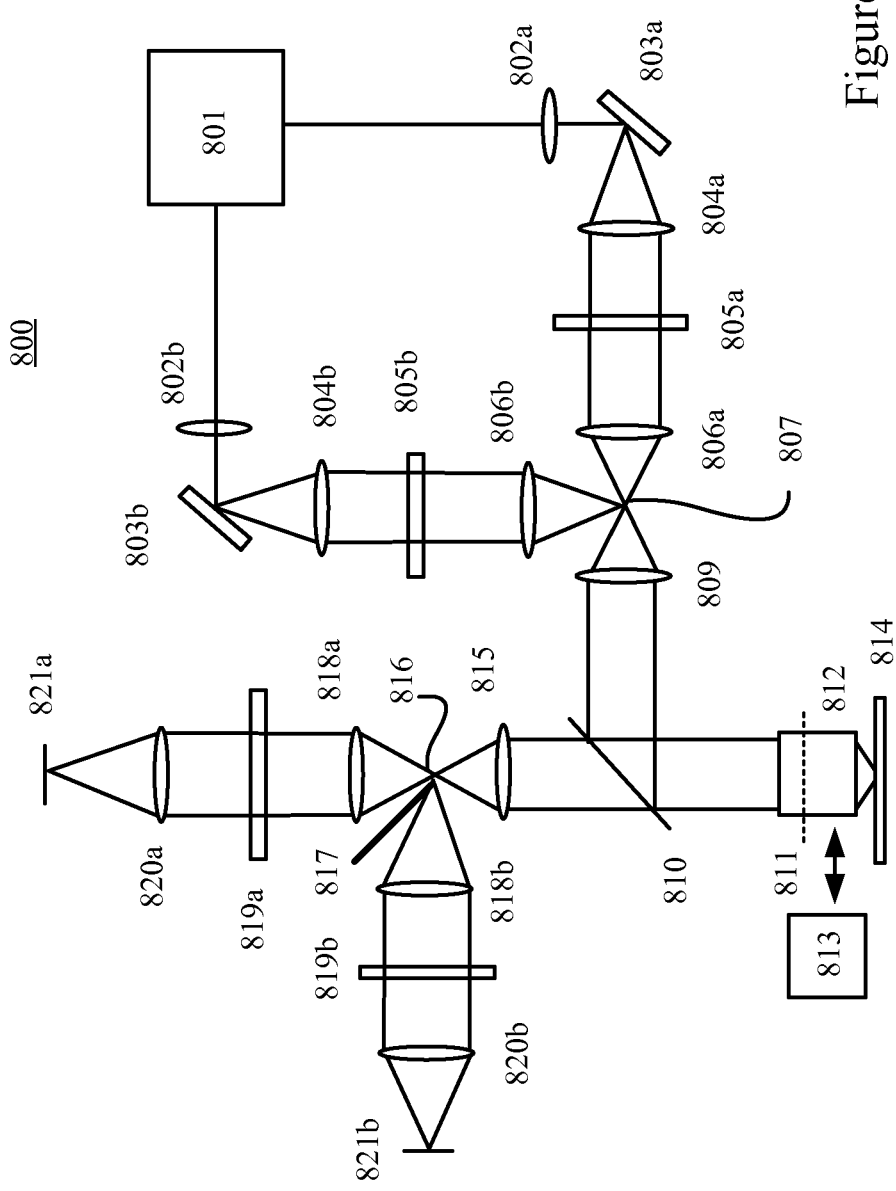

700
Illumination source
709
Channel one
illumination relay
715
Channel two
illumination relay
720
Inspected object
730
Image relay optics
740
Channel one image
mode relay
755
Channel two image
mode relay
760
Sensor
770
Data
780

Figure 7


800
801
802a
803a
804a
805a
806a
807
809
802b
804b
805b
806b
803b
821a
818a
816
815
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814
820a
819a
817
818b
810
811
819b
820b
821b
813

Figure 8

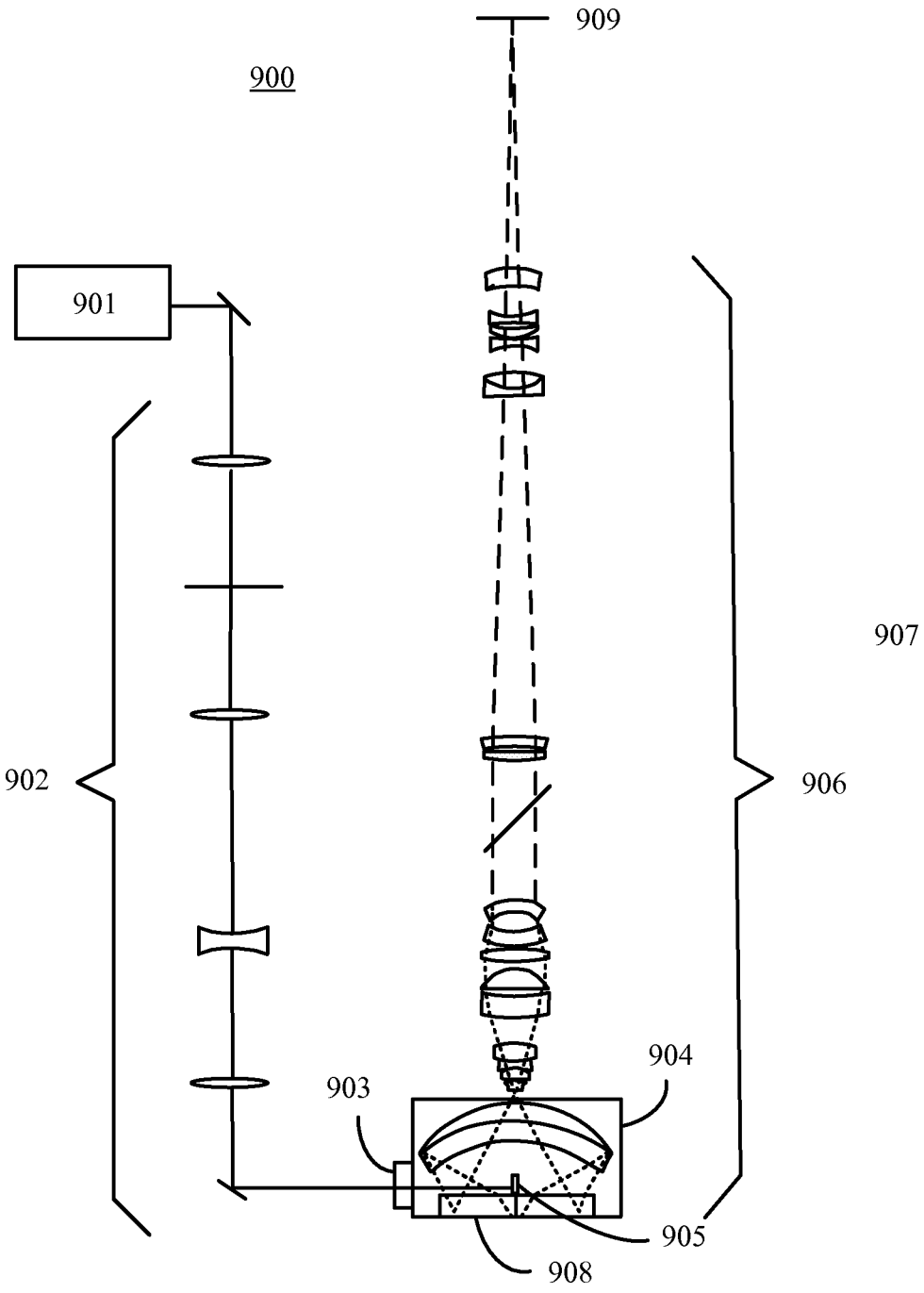

Figure 9

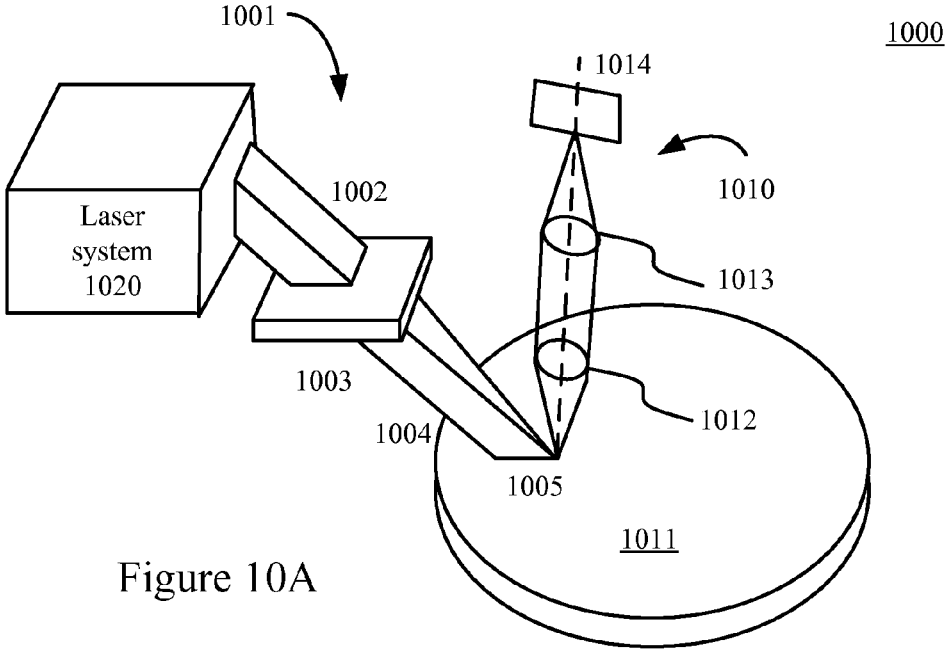

Figure 10A

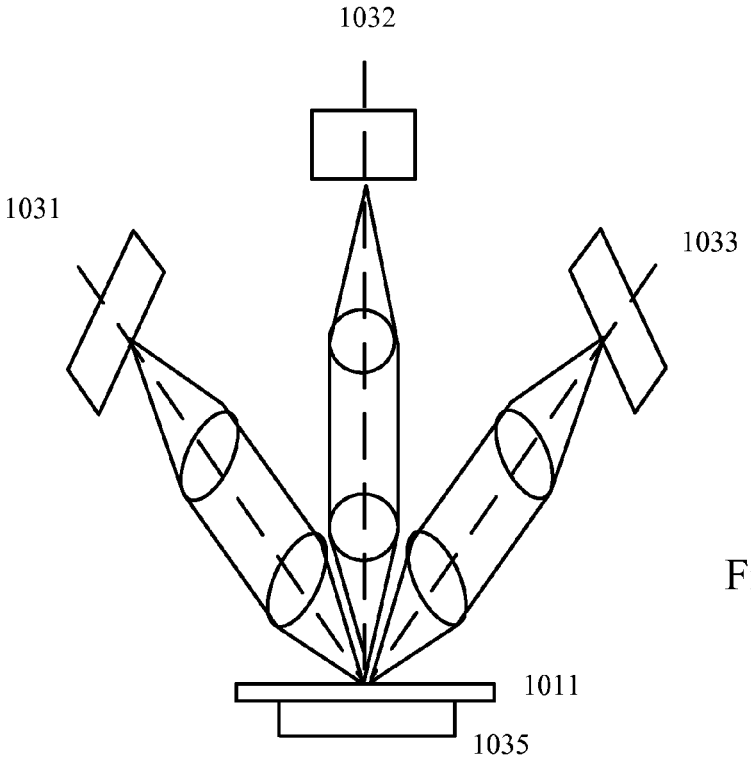

Figure 10B

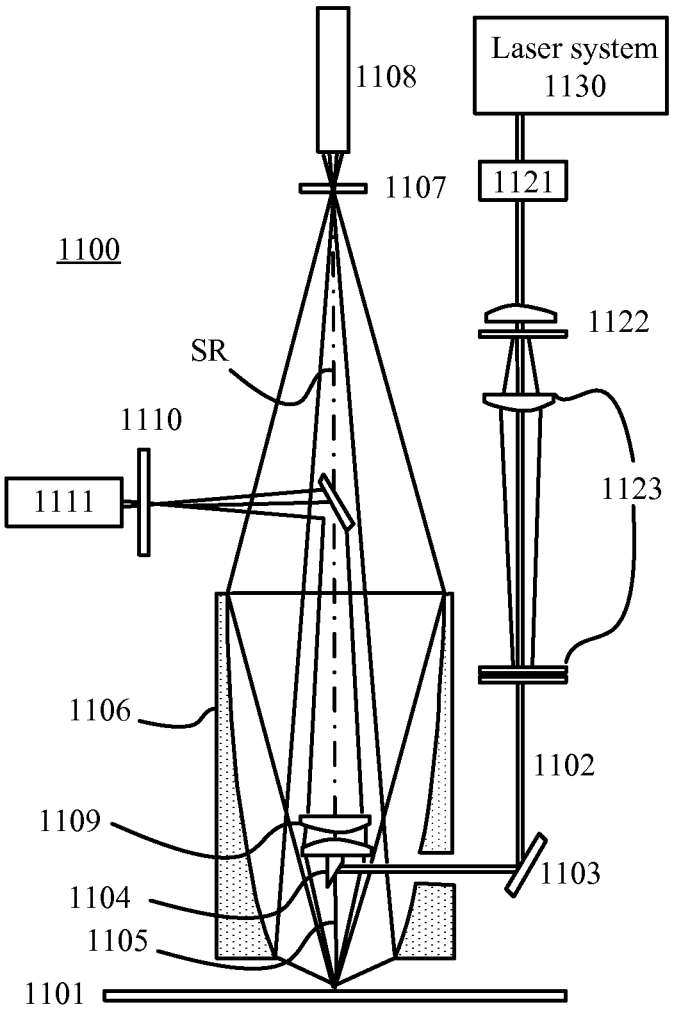
1108
Laser system
1130
1107
1121
1100
1122
SR
1110
1111
1123
1106
1102
1109
1103
1104
1105
1101

Figure 11

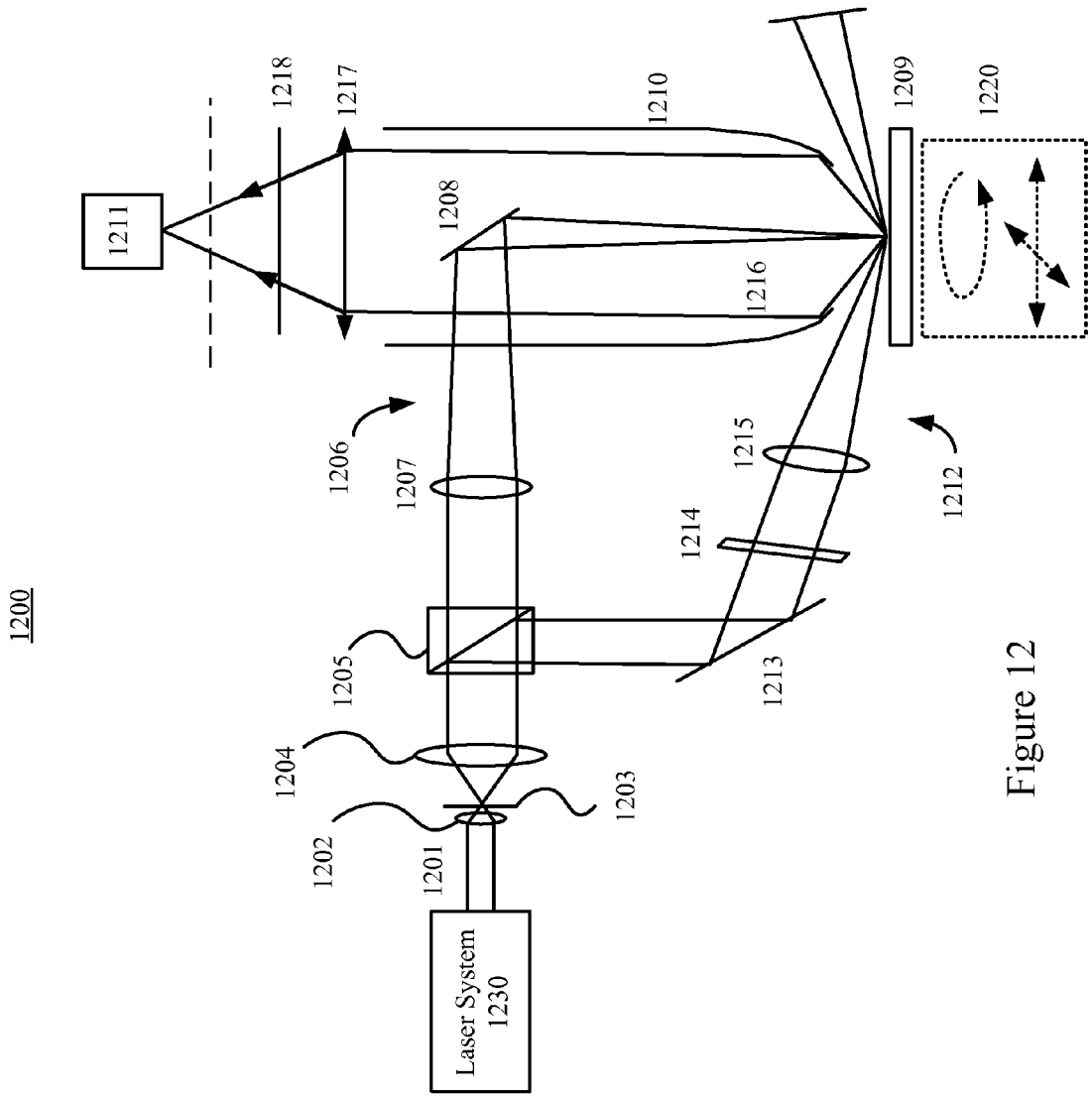
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1220
Laser System
1230

Figure 12

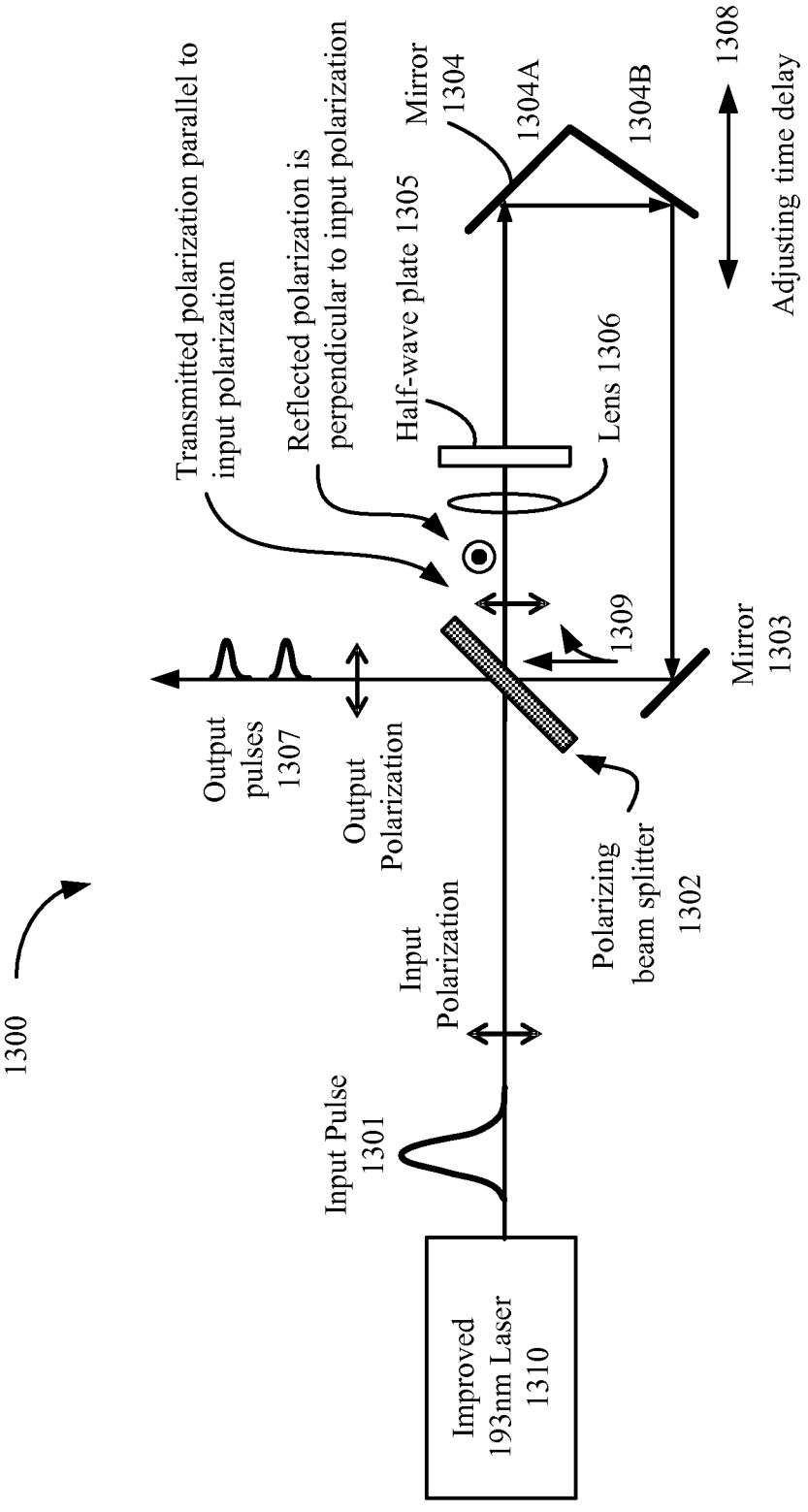
1300
Improved 193nm Laser 1310
Input Pulse 1301
Input Polarization
Output Polarization
Output pulses 1307
Polarizing beam splitter 1302
Mirror 1303
1309
Lens 1306
Half-wave plate 1305
Mirror 1304
1304A
1304B
1308
Adjusting time delay
Transmitted polarization parallel to input polarization
Reflected polarization is perpendicular to input polarization

Figure 13

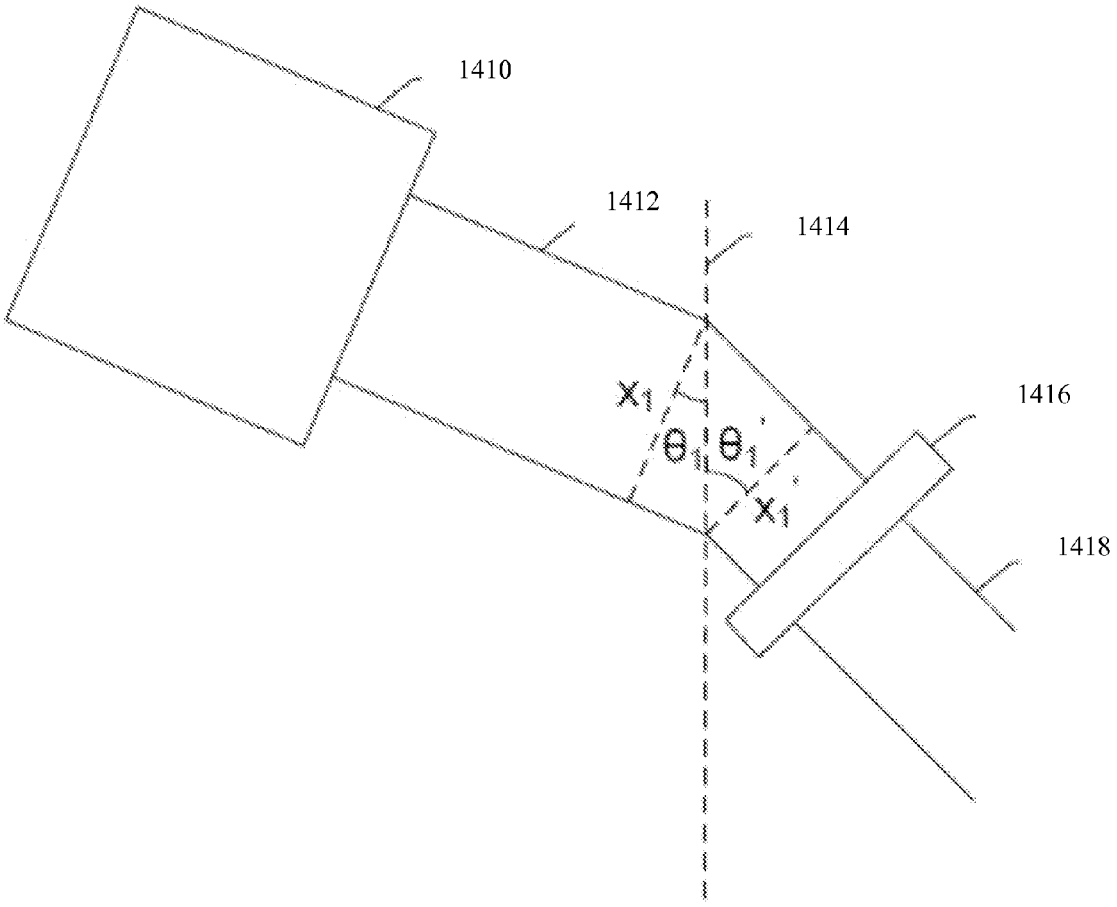

Figure 14

193NM LASER AND INSPECTION SYSTEM

PRIORITY APPLICATION

This application is a continuation of U.S. patent application Ser. No. 14/158,615 entitled "193 NM LASER AND INSPECTION SYSTEM" filed Jan. 17, 2014 which claims priority of U.S. Provisional Patent Application 61/756,209, filed on Jan. 24, 2013 and incorporated by reference herein.

RELATED APPLICATION

The present application is related to U.S. patent application Ser. No. 13/797,939, entitled "Solid-State Laser and Inspection System Using 193 nm Laser", filed on Mar. 12, 2013 by Chuang et al. and incorporated by reference herein.

BACKGROUND OF THE DISCLOSURE

1. Field of the Disclosure

This disclosure relates to a laser and specifically to a solid state or fiber laser that generates radiation near 193 nm and is suitable for use in inspection of photomasks, reticles, and/or wafers. The laser may be pulsed (Q-switched or mode-locked) or CW (continuous wave).

2. Related Art

Excimer lasers for generating light at 193 nm are well known in the art. Unfortunately, such lasers are not well suited to inspection applications because of their low laser pulse repetition rates and their use of toxic and corrosive gases in their lasing medium, which leads to high cost of ownership.

Solid state and fiber lasers for generating light near 193 nm are also known. Exemplary lasers use two different fundamental wavelengths or the eighth harmonic of the fundamental, either of which requires lasers or materials that are expensive or are not in high volume production. Moreover, most of these lasers have very low power output and are limited to laser pulse repetition rates of a few MHz or less.

Therefore, a need arises for a laser and preferably to a solid state or fiber laser that generates radiation near 193 nm and is suitable for use in inspection of photomasks, reticles, and/or wafers. Notably, such inspections at high speeds often require minimum laser pulse repetition rates of multiple MHz (e.g. greater than 50 MHz in some cases).

SUMMARY OF THE DISCLOSURE

A laser for generating an output wavelength of approximately 193.4 nm is described. This laser includes a fundamental laser, an optical parametric generator, a fourth harmonic generator, and a frequency mixing module. The optical parametric generator, which is coupled to the fundamental laser, can generate a down-converted signal. The fourth harmonic generator, which is coupled to the optical parametric generator, can generate a fourth harmonic. The frequency mixing module, which is coupled to the optical parametric generator and the fourth harmonic generator, can generate a laser output of a frequency equal to a sum of the fourth harmonic and twice a frequency of the down-converted signal. Notably, the frequency mixing module comprises two non-linear crystals. In one embodiment, a first non-linear crystal is configured to generate a frequency equal to a sum of the fourth harmonic and the frequency of down-converted signal by type-II conversion, and a second non-linear crystal is configured to generate the frequency equal to the sum of the fourth harmonic and the twice the frequency of the down-converted signal by type-I conversion.

Another laser for generating an output wavelength of approximately 193.4 nm is described. This laser includes a fundamental laser, first and second frequency doubling modules, an optical parametric generator, and a frequency mixing module. The first frequency doubling module, which is coupled to the fundamental laser, can generate a second harmonic. The second frequency doubling module, which is coupled to the first frequency doubling module, can generate a fourth harmonic. The optical parametric generator, which is coupled to the first frequency doubling module or the fundamental laser, can generate a down-converted signal. The frequency mixing module, which is coupled to the optical parametric generator and the second frequency doubling module, can generate a laser output of a frequency equal to a sum of the fourth harmonic and twice a frequency of the down-converted signal. Notably, the frequency mixing module comprises two non-linear crystals. In one embodiment, a first non-linear crystal is configured to generate a frequency equal to a sum of the fourth harmonic and a frequency of the down-converted signal by type-I conversion, and a second non-linear crystal is configured to generate the frequency equal to the frequency of the sum of the fourth harmonic and the twice the down-converted signal by type-II conversion.

Yet another laser for generating an output wavelength of approximately 193.4 nm is described. This laser includes a fundamental laser, a frequency doubling module, a frequency combiner, an optical parametric generator, and a frequency mixing module. The frequency doubling module, which is coupled to the fundamental laser, can generate a second harmonic. The frequency combiner, which is coupled to the frequency doubling module, can generate a third harmonic. The optical parametric generator, which is coupled to the frequency doubling module or the frequency combiner, can generate a down-converted signal. The frequency mixing module, which is coupled to the optical parametric generator and the frequency combiner, can generate a laser output of a frequency equal to a sum of the third harmonic and twice a frequency of the down-converted signal.

These 193.4 nm lasers can be constructed using components that are readily available and are relatively inexpensive. For example, the fundamental laser used in the various described embodiments can generate a fundamental frequency of approximately 1064.3 nm, approximately 1053 nm, approximately 1047 nm, or approximately 1030 nm. These fundamental lasers are readily available at reasonable prices in various combinations of power and repetition rate. The fundamental laser can include a laser diode or a fiber laser.

The optical parametric generator, implemented as an optical parametric amplifier (OPA) or as an optical parametric oscillator (OPO), can include a periodically poled non-linear optical crystal. Exemplary periodically poled non-linear crystals can be formed from lithium niobate (LN), magnesium-oxide doped lithium niobate (Mg:LN), stoichiometric lithium tantalate (SLT), magnesium-oxide doped stoichiometric lithium tantalate (Mg:SLT), or potassium titanyl phosphate (KTP).

The down-converted signal generated by the optical parametric generator has a signal wavelength of one of approximately 1380 nm to 1612 nm, 1416 nm, 818 nm to 918 nm, and 846 nm to 856 nm.

The frequency mixing module can include a cesium lithium borate (CLBO) crystal, a beta barium borate (BBO) crystal, or a lithium triborate (LBO) crystal. In one exemplary mixing technique, the fourth harmonic at a wavelength of

approximately 266 nm is mixed with the down-converted signal at approximately 1416 nm (infra-red light) to generate a wavelength of approximately 224 nm. The approximately 224 nm light is then recombined with the down-converted signal to generate a wavelength of approximately 193 nm. These two frequency mixing stages contribute to the overall high efficiency and stability of the 193 nm laser. In some preferred embodiments, these two frequency mixing stages can include CLBO crystals, which at a temperature near 100° C., can perform these two conversions with high efficiency (e.g. non-linear coefficients can be approximately 0.5 to 1 pm V^{-1}) and small walk-off angles. In one embodiment, type II mixing in CLBO can be used for the conversion stage that generates the approximately 224 nm wavelength followed by type-I mixing in CLBO to generate the approximately 193 nm wavelength. In another embodiment, type-I mixing in CLBO can be used for the conversion stage that generates the approximately 224 nm wavelength followed by type-II mixing in CLBO to generate the approximately 193 nm wavelength. In some embodiments, one or both of these two frequency mixing stages may be performed using a non-linear optical crystal other than CLBO, such as BBO (beta barium borate) or LBO (lithium triborate).

The improved lasers for generating an output wavelength of approximately 193.4 nm described herein can be continuous-wave lasers, Q-switched lasers, mode-locked lasers, or quasi-continuous-wave lasers. Compared to eighth harmonic lasers, these improved lasers are significantly less expensive, and have longer life and better cost of ownership. Moreover, compared with low repetition rate lasers, these improved lasers can significantly simplify the illumination optics of the associated inspection system.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A, **1**B, and **1**C show block diagrams of exemplary improved 193 nm lasers.

FIG. **1**D shows a table of exemplary wavelength ranges for the improved 193 nm lasers shown in FIGS. **1**A and **1**B.

FIG. **1**E shows a table of exemplary wavelength ranges for the improved 193 nm laser shown in FIG. **1**C.

FIG. **2** shows one embodiment of a fourth harmonic generator.

FIG. **3** shows one embodiment of a frequency mixer module.

FIGS. **4**A and **4**B show some embodiments of frequency mixers that can be used in the improved 193 nm lasers.

FIG. **5** illustrates an exemplary amplifier module in which a seed laser can generate stabilized, narrow-band seed laser light.

FIG. **6** illustrates an exemplary OPO/OPA configured to generate the down-converted signal at frequency ω_s.

FIG. **7** shows a reticle, photomask, or wafer inspection system that simultaneously detects two channels of image or signal on one sensor.

FIG. **8** illustrates an exemplary inspection system including multiple objectives and one of the above-described improved 193 nm lasers.

FIG. **9** illustrates the addition of a normal incidence laser dark-field illumination to a catadioptric imaging system.

FIG. **10**A illustrates a surface inspection apparatus that includes an illumination system and a collection system for inspecting areas of a surface.

FIG. **10**B illustrates an exemplary array of collection systems for a surface inspection apparatus.

FIG. **11** illustrates a surface inspection system that can be used for inspecting anomalies on a surface.

FIG. **12** illustrates an inspection system configured to implement anomaly detection using both normal and oblique illumination beams.

FIG. **13** illustrates an exemplary pulse multiplier for use with the above-described improved 193 nm laser in an inspection or metrology system.

FIG. **14** illustrates a coherence reducing subsystem for use with the above-described improved 193 nm laser in an inspection or metrology system.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. **1**A shows a block diagram of an exemplary improved 193 nm laser **100**A. In laser **100**A, a fundamental laser **102** operating at a frequency ω can generate fundamental light **128** (called the "fundamental" in the industry). In one embodiment, the frequency ω (the fundamental) may correspond to an infra-red wavelength near 1064 nm. Note that when a wavelength is used herein without qualification, such wavelength refers to the vacuum wavelength of the light. An exemplary fundamental laser **102** can be implemented by a laser using a Nd:YAG (neodymium-doped yttrium aluminum garnate) lasing medium or a Nd-doped yttrium orthovanadate lasing medium or by an ytterbium-doped fiber laser. Suitable fundamental lasers are commercially available as pulsed (Q-switched or mode-locked) or CW (continuous wave) from Coherent Inc. (including models in the Paladin family with repetition rates of 80 MHz and 120 MHz), Newport Corporation (including models in the Explorer family) and other manufacturers. Laser power levels for such fundamental lasers can range from milliWatts to tens of Watts or more.

In laser **100**A, the fundamental **128** is directed towards an optical parametric generator, e.g. an optical parametric oscillator or an optical parametric amplifier (OPO/OPA) **116**. OPO/OPA **116** can down-convert part of the fundamental light **128** to a down-converted signal **129** of frequency ω_s. In some preferred embodiments, the wavelength corresponding to ω_s is approximately 1416 nm (e.g. within a range from about 1330 nm to about 1612 nm, within a range from about 1378 nm to 1461 nm, or within a range from about 1413 nm to about 1417 nm).

In some embodiments, only part of the fundamental **128** is consumed in the down-conversion process. In such embodiments, the unconsumed part of the fundamental light **128**, i.e. the unconsumed fundamental **130**, is directed to a fourth harmonic generation module **103**. Module **103** (described in further detail below) typically includes multiple frequency conversion stages to generate the 4^{th} harmonic (4ω) from the unconsumed fundamental (ω). This 4^{th} harmonic (4ω) can be combined with the down-converted signal **129** in a frequency mixing module **118** to create a laser output **140** having a frequency substantially equal to the sum of 4ω and $2\omega_s$. In some embodiments, the output wavelength of the laser output **140** is substantially equal to 193.368 nm. In other embodiments, the output wavelength is between approximately 190 nm and 200 nm or between approximately 192 nm and 195 nm.

FIG. **1**B shows a block diagram of an alternative improved 193 nm laser **100**B. In this embodiment, the fundamental (ω) (generated by any of the above-mentioned lasers) is directed to a first frequency doubling module **110** to generate a second harmonic (2ω). The unconsumed fundamental output by the first frequency doubling module **110** can be directed to the OPO/OPA **116**, which in turn generates the down-converted signal ω_s. As noted above, the wavelength of the down-converted signal ω_s is approximately 1416 nm (e.g. within a

range from about 1330 nm to about 1612 nm, within a range from about 1380 nm to 1461 nm, or within a range from about 1413 nm to about 1417 nm).

The second harmonic (2ω) generated by the first frequency doubling module **110** is directed to a second frequency doubling module **112** to generate a fourth harmonic (4ω). The frequency mixing module **103** can combine the fourth harmonic (4ω) and the down-converted signal (ω_s) to create the laser output **140** having a frequency approximately equal to the sum of 4ω and $2\omega_s$. As noted above, in some embodiments, this output wavelength is approximately equal to 193.368 nm. In other embodiments, the output wavelength is between approximately 190 nm and 200 nm or between approximately 192 nm and 195 nm.

In yet another embodiment, the fundamental (ω) output by the fundamental laser **102** can be split into two portions. One portion is directed to the first frequency doubling module **110**, and the other portion is directed to the OPO/OPA **116** (shown by arrow **109**). Thus, in this embodiment, the unconsumed fundamental ω output by the first frequency doubling module **110** is not directed to OPO/OPA **116**. The second frequency doubling module **112** and the OPO/OPA **116** are both still coupled to the frequency mixing module **103**, as shown in FIG. **1**B. Substantially similar wavelengths are used and generated in this modified embodiment as in the above-described improved 193 nm laser **100**B.

FIG. **1**D shows a table of exemplary wavelength ranges (in nm) for the improved 193 nm lasers shown in FIGS. **1**A and **1**B. For each fundamental laser type, an exemplary short-wavelength fundamental and an exemplary long-wavelength fundamental are shown, along with the wavelengths corresponding to the harmonics and the down-converted signal required for the desired output wavelength (193.4 nm in the example shown in the table). The exact wavelength of a fundamental laser depends on many factors including the exact composition of the lasing medium, the operating temperature of the lasing medium, and the design of the optical cavity. Two lasers using the same laser line of a given lasing medium may operate at wavelengths that differ by a few tenths of 1 nm or a few nm due to the aforementioned and other factors. One skilled in the appropriate arts would understand how to choose the appropriate wavelength for the down-converted signal in order to generate the desired output wavelength from any fundamental wavelength close to those listed in the table. Similarly, if the desired output wavelength differs from 193.4 nm by a few nm, the desired output wavelength can also be achieved by an appropriate adjustment of the wavelength for the down-converted signal.

FIG. **1**C shows another alternative embodiment of an improved 193 nm laser **100**C. In this embodiment, the fundamental ω output by the fundamental laser **102** is directed to the frequency doubling module **110** to generate a second harmonic 2ω. The fundamental ω may be generated by any of the above-mentioned lasers. The portion of the fundamental ω not consumed in the frequency doubling module **110** and the second harmonic 2ω are then directed to a frequency combiner **133**, which generates a third harmonic 3ω.

The second harmonic 2ω not consumed by the frequency combiner **133** is then directed to an OPO/OPA **136** to generate a down-converted signal **132** having a frequency ω_s. In one modified embodiment (shown by arrow **140**), a portion of the second harmonic 2ω can be taken directly from the output of the frequency doubling module **110** and directed to the OPO/OPA **136** (i.e. instead of taking the unconsumed second harmonic from the output of the frequency combiner **133**). In some embodiments, the wavelength of the down-converted signal **132** is approximately 850 nm (e.g. within a range from about 818 nm to about 918 nm, or within a range from about 836 nm to 867 nm, or within a range from about 846 nm to about 856 nm). Note that the exact wavelength selected for ω_s depends on the exact wavelength of the fundamental laser and the desired output wavelength. Different fundamental lasers of the same type may differ in wavelength by a few tenths of a nm due to different lasing medium temperatures, lasing medium composition variations, and other small differences in the laser cavity design. In some embodiments, an output wavelength within a few nm of 193 nm is possible using the improved 193 nm laser, such as an output wavelength between 192 nm and 195 nm or between 190 nm and 200 nm.

A frequency mixing module **138** can combine the third harmonic 3ω and the down-converted signal **132** (ω_s) to create a laser output **150** at a wavelength that corresponds to a frequency substantially equal to the sum of 3ω and $2\omega_s$. In some embodiments, this output wavelength is substantially equal to 193.368 nm. In other embodiments, this output wavelength is between approximately 190 nm and 200 nm or between approximately 192 nm and 195 nm. In some embodiments, the frequency mixing module **138** may include a CLBO crystal to mix 3ω and ω_s to create the sum of these two frequencies at a wavelength of approximately 250 nm (when ω corresponds to a wavelength of approximately 1064 nm). In some embodiments, the frequency mixing module **138** may further include a BBO, KBBF (Potassium beryllium fluoroborate) or KBO (potassium pentaborate tetrahydride) crystal to mix the sum of $3\omega+\omega_s$ with ω_s to create the laser output **150** (corresponding to a wavelength of approximately 193.4 nm in one preferred embodiment). FIG. **1**E shows a table of exemplary wavelength ranges (in nm) for the improved 193 nm laser shown in FIG. **1**C. FIG. **1**E shows analogous information to that shown in FIG. **1**D for the improved 193 nm lasers of FIGS. **1**A and **1**B. See the detailed explanation above for FIG. **1**D.

FIG. **2** shows a preferred embodiment of a fourth harmonic generator **200**. The fundamental **201** at frequency ω is converted to the second harmonic (2ω) **202**A by a first frequency doubling module **202**. The second harmonic **202**A is converted to the fourth harmonic (4ω) **203**A by a second frequency doubling module **203**. The unconsumed fundamental **202**B and the unconsumed second harmonic **203**B not used within the first frequency doubling module **202** and the second frequency doubling module **203**, respectively, may be output separately by these modules.

In one preferred embodiment of fourth harmonic generator **200**, the second harmonic generation module **202** may comprise a LBO crystal for frequency conversion. In other embodiments, the second harmonic generation module **202** may comprise a CLBO, BBO, or other non-linear crystal for frequency conversion. In one preferred embodiment of fourth harmonic generator **200**, the fourth harmonic generation module **203** may comprise a CLBO crystal for frequency conversion. In other embodiments, the fourth harmonic generation module **203** may comprise a BBO or other non-linear crystal for frequency conversion.

FIG. **3** shows a preferred embodiment of a frequency mixer module **300**. In frequency mixer module **300**, a first frequency mixer **302** receives a fourth harmonic (4ω) **301**A and a down-converted signal (ω_s) **301**B to generate a sum frequency **303**A at a frequency equal to the sum of 4ω and ω_s. The sum frequency **303**A and an unconsumed signal **303**B at frequency of ω_s are directed to a second frequency mixer **304**, which generates a laser output **305** at a frequency of $4\omega+2\omega_s$. In some embodiments, the first frequency mixer **302** directs an unconsumed fourth harmonic **303**C away from the second frequency mixer **304**. In other embodiments, the unconsumed

fourth harmonic **303**C can be passed to the second frequency mixer **304** because, in those embodiments, the polarization of the second frequency mixer **304** is oriented such that it has little or no effect on the generation of the laser output **305**.

In preferred embodiments, the sum frequency **303**A is a frequency that is equivalent to a wavelength of approximately 224 nm. In some embodiments, the sum frequency **303**A is substantially equal to the frequency corresponding to a wavelength of 223.95 nm. In other embodiments, the sum frequency **303**A is a frequency corresponding to a wavelength in the range from approximately 221 nm to approximately 229 nm. In yet other embodiments, the sum frequency **303**A is a frequency corresponding to a wavelength in the range from approximately 222 nm to approximately 226 nm. In preferred embodiments, frequency mixer **302** comprises a CLBO crystal for frequency conversion. In preferred embodiments, frequency mixer **304** comprises a CLBO crystal for frequency conversion.

Note that the frequency mixing module **138** (FIG. **1**C) may be implemented in a similar manner to that illustrated in FIG. **3** for frequency mixing module **300**, except that its inputs are the third harmonic (3ω) and the signal frequency (ω_s) instead of the fourth harmonic (4ω) and the signal frequency (ω_s). Some appropriate crystals for use in the frequency mixers **302** and **304** are described above. In particular, note that when frequency mixing module **300** is used for frequency mixing module **138**, CLBO cannot be used in frequency mixer **304** for generating a wavelength near 193.4 nm because it does not phase match. As noted above, BBO, or another non-linear crystal, must be used in frequency mixer **304** in this case.

Note that in any of the embodiments shown in FIGS. **1**A, **1**B, **1**C, **2**, and **3**, mirrors may be used to direct the fundamental or other wavelengths as needed. Prisms, beam splitters, beam combiners and dichroic coated mirrors, for example, may be used to separate and combine beams as necessary. Various combinations of mirrors and beam splitters may be used to separate and route the various wavelengths between different frequency generators and mixers in any appropriate sequence. The faces of frequency conversion crystals and prisms may be cut at an angle approximately or substantially equal to Brewster's angle for an incident wavelength in order to minimize or control reflection without using an anti-reflection coating. This cutting can be particularly advantageous for those surfaces where UV radiation is incident, because anti-reflection coatings may degrade when exposed to UV and thus may degrade the reliability of the laser if used on such surfaces. Waveplates or other optical elements may be used to rotate the polarization of any of the wavelengths as needed to align the polarization with the appropriate crystal axis of the next frequency conversion or frequency mixing stage.

FIGS. **1**A, **1**B, and **1**C illustrate various improved lasers for generating a frequency substantially equal to four times the fundamental frequency (three times the fundamental frequency for FIG. **1**C) plus two times the signal frequency, where the signal frequency is created by down-conversion from the fundamental (down-conversion from the second harmonic in FIG. **1**C). Other laser embodiments similar to those described above for generating four times the fundamental frequency plus two times the signal frequency or three times the fundamental frequency plus two times the signal frequency are possible and are within the scope of this invention.

The above-described figures are not meant to represent the actual physical layout of the components. The above-described figures show the main optical modules involved in the process, but do not show every optical element. One skilled in the appropriate arts would understand how to build the improved laser from the above-described figures and their associated descriptions. It is to be understood that more or fewer mirrors or prisms may be used to direct the light where needed. Lenses and/or curved mirrors may be used to focus the beam waist to foci of substantially circular or elliptical cross sections inside or proximate to the non-linear crystals where appropriate. Prisms, gratings or diffractive optical elements may be used to steer or separate the different wavelengths at the outputs of each frequency convertor or mixer module when needed. Prisms, coated mirrors, or other elements may be used to combine the different wavelengths at the inputs to the frequency convertors and mixers as appropriate. Beam splitters or coated mirrors may be used as appropriate to divide one wavelength into two beams. Filters may be used to block undesired wavelengths at the output of any stage. Waveplates may be used to rotate the polarization as needed. Other optical elements may be used as appropriate. U.S. patent application Ser. No. 13/293,485, entitled "High Damage Threshold Frequency Conversion System", filed on May 17, 2012, and incorporated by reference herein, describes various optical elements particularly suited to use in the frequency conversion stages that generate UV wavelengths. In some cases, it may be acceptable to allow unconsumed light from one frequency conversion stage to pass to the next stage even though that light is not needed in the subsequent stage. This may be acceptable if the power density is low enough not to cause damage and if there is little interference with the desired frequency conversion process (for example because of no phase matching at the crystal angle or due to the polarization of the light). One skilled in the appropriate arts would understand the various tradeoffs and alternatives that are possible in the implementation of the improved laser.

In a preferred embodiment, the first frequency doubling module **110** (FIG. **1**B) that generates the second harmonic can include a Lithium triborate (LBO) crystal, which is substantially non-critically phase-matched at temperature of about 149° C. to produce light at approximately 532 nm. In another embodiment, the second frequency doubling module **112** (FIG. **1**B) that generates the fourth harmonic and the frequency mixers **302** and **304** (FIG. **3**) can use critical phase matching in Cesium Lithium Borate (CLBO), beta-Barium Borate (BBO), LBO, or other non-linear crystals. In preferred embodiments, the second frequency mixer **304** includes a CLBO crystal that is critically phase matched with a high D_{eff} (approximately 0.5 to 1 pm/V) and a low walk-off angle (less than about 35 mrad) at a temperature of approximately 100° C. This temperature is a convenient temperature to use because it minimizes absorption of water by the CLBO crystal. However, higher and lower temperatures may be used with appropriate adjustment of the angle of the crystal relative to the incident light. In some embodiments, the second frequency mixer **304** includes BBO, which has a larger walk-off angle (approximately 100 mrad) and a larger D_{eff} (approximately 1 to 2 pm/V) compared with CLBO. In preferred embodiments, the frequency mixer **302** includes a CLBO crystal that is critically phase matched with a high D_{eff} (approximately 0.8 pm/V) and a low walk-off angle (less than about 40 mrad) at a temperature of approximately 100° C. In that case, the second frequency mixer **304** can include BBO, which has a larger walk-off angle (approximately 96 mrad) and a larger D_{eff} (approximately 1 to 2 pm/V) compared with CLBO.

The frequency doubling module **112** and the frequency mixers **302** and **304** may advantageously use some, or all, of the methods and systems disclosed in co-pending U.S. patent application Ser. No. 13/412,564, filed on Mar. 5, 2012 and

entitled "Laser with high quality, stable output beam, and long-life high-conversion-efficiency non-linear crystal" by Dribinski et al. U.S. patent application Ser. No. 13/412,564 claims priority from U.S. Provisional Application No. 61/510,633, entitled "Mode-locked UV laser with high quality, stable output beam, long-life high conversion efficiency non-linear crystal and a wafer inspection system using a mode-locked laser", which was filed on Jul. 22, 2011. Both of these patent applications are incorporated by reference as if fully set forth herein.

Any of the harmonic generation stages (such as those performed by frequency doubling modules **110** and **112**) and frequency mixing stages (such as performed by frequency mixers **302** and **304**) may include one or more protective environments, such as those described in PCT Published Patent Application WO 2009/082460, entitled "Enclosure for controlling the environment of optical crystals", by J. Joseph Armstrong, and published on Jul. 2, 2009. This PCT publication is incorporated by reference as if fully set forth herein. Note that a single protective environment may enclose multiple stages or a single stage.

Further note that any of the harmonic generators (e.g. frequency doubling modules **110** and **112**) may advantageously use hydrogen-annealed non-linear crystals. Such crystals may be processed as described in U.S. Provisional Application 61/544,425 filed on Oct. 7, 2011 by Chuang et al. and in co-pending U.S. patent application Ser. No. 13/488,635 filed on Jun. 1, 2012 by Chuang et al. These applications are incorporated by reference as if fully set forth herein. The hydrogen annealed crystals may be particularly useful in those stages involving deep UV wavelengths, including the frequency doublers **112** and **203** and the frequency mixers **302** and **304**.

FIGS. **4**A and **4**B show some preferred embodiments of frequency mixers that can be used in the improved lasers described above. FIG. **4**A illustrates one embodiment of a frequency mixer **400**A in which type-II mixing is used for the first frequency mixing stage and type-I mixing is used for the final frequency mixing stage. Typically, three-wave mixing is done in a birefringent crystalline material (i.e. the refractive index depends on the polarization and direction of the light that passes through), where the polarizations of the fields and the orientation of the crystal are chosen such that the phase-matching condition is achieved. Typically, a birefringent crystal has three axes, one or two of which have a different refractive index than the other one(s). For example, uniaxial crystals have a single extraordinary (e) axis and two ordinary axes (o). If the two input frequencies have the same polarization (usually parallel to an o axis of the crystal), the phase matching is called "type-I phase-matching" and if their polarizations are perpendicular, it is called "type-II phase-matching". However, other conventions exist that specify further which frequency has what polarization relative to the crystal axis.

The first frequency mixing stage comprises a non-linear crystal **402**, such as CLBO. The fourth harmonic and the signal wavelength enter the crystal **402** approximately collinearly in direction **410** and are focused to beam waists inside or proximate to this crystal (beam waists not shown). The signal wavelength is polarized with its electric-field vector in a direction shown by an arrow **420**. The fourth harmonic is polarized substantially perpendicularly to the signal wavelength. The extraordinary (e) axis of the non-linear crystal **402** is oriented substantially parallel to the direction **420**, as shown by an arrow **425**. The plane containing the ordinary (o) axes of the non-linear crystal **402** are oriented substantially perpendicular to the direction **420**. The o axes of the crystal **402** are rotated at an angle relative to the propagation direction of the light in the crystal so as to achieve phase matching. For type-II matching in CLBO at a temperature of approximately 100° C. with a signal wavelength near 1416 nm and a fourth harmonic wavelength near 266 nm, this angle is approximately 58.9°, and for BBO at approximately 100° C. with the same wavelengths, this angle is approximately 45.7°. One skilled in the appropriate arts understands how to choose different combinations of temperature and angle to achieve phase matching.

In some embodiments, the input surface **442** of crystal **402** is cut so as to be approximately at a Brewster's angle relative to the fourth harmonic (i.e. the direction **410**). This angle minimizes reflection of the fourth harmonic wavelength without needing any anti-reflection coating on the input surface **442**. In some embodiments, the input surface **442** may have an anti-reflection coating to reduce the reflected light at the fourth harmonic and/or the signal wavelengths. The output surface **452** of the crystal **402** may be coated or uncoated. The advantage of not coating is that coatings can have a short lifetime when exposed to intense UV radiation.

The output light **412** from crystal **402** is directed by optics **403** to the final frequency mixing stage, which includes a non-linear crystal **404**. Note that three wavelengths exit crystal **402**: the signal wavelength, the fourth harmonic wavelength, and a wavelength of the sum of the signal and the fourth harmonic. Because of the small walk-off angle, these three wavelengths are traveling approximately, but not exactly, collinearly. Optics **403** may include lenses, mirrors, prisms, beam splitters, and/or other optical elements. The optics **403** may refocus the beam waist inside, or proximate to, the crystal **404**. In some embodiments, the optics **403** may approximately compensate for the walk-off so as to make the wavelengths more collinear as they enter crystal **404**. In some embodiments, the optics **403** may separate out any unconsumed fourth harmonic. Other embodiments of the optics **403** may not separate the unconsumed fourth harmonic because it is polarized perpendicular to the polarization direction **421** and therefore will not be phase matched in the crystal **404**. The polarization direction **421** is the direction of the electric field of both the signal wavelength and the wavelength of the sum of the signal and fourth harmonic wavelength. The polarization direction **421** is substantially parallel to the polarization direction **420** of the input signal wavelength. In some embodiments, the optics **403** may relatively delay by different amounts of time the pulses at different wavelengths so that they arrive substantially simultaneously inside the crystal **404**. In other embodiments, the pulses are sufficiently long that the pulses overlap inside the crystal **404** without wavelength-dependent delays being incorporated into the optics **403**. In some embodiments, the optics **403** may be omitted. The optics **403** may be omitted if the Rayleigh ranges of all the wavelengths are long enough that efficient mixing occurs in both crystals **402** and **403** without refocusing, provided also that the walk-off is small enough relative to the beam diameters, and the pulse lengths are long enough to have substantial overlap of the different wavelengths inside both crystals. The optics **403** may be coated or uncoated.

The crystal **404** may have its input surface **444** oriented at approximately a Brewster's angle for the wavelength corresponding to the sum of the signal and fourth harmonic. In such embodiments, the surface **444** can be uncoated, which has the advantage of reducing the susceptibility to damage by high intensity UV radiation. In other embodiments, the surface **444** may have an anti-reflection coating. In some embodiments, the surface **444** may be substantially perpendicular to the output light **412**. The crystal **404** is oriented so

that the plane containing its o axes is substantially parallel to the plane containing the polarization direction **421** and the direction of the output light **412** coming from the crystal **402**. The e axis of crystal **404** is substantially perpendicular to the polarization direction **421**. One o axis of the crystal **404** is rotated to an angle relative to direction of the output light **412** so as to achieve phase matching. For type I matching in CLBO at approximately 100° C. with wavelengths of approximately 1416 nm and 224 nm, this angle is approximately 65.4°. For BBO at approximately 100° C. for similar wavelengths, this angle is approximately 50.0°. In some embodiments, the output surface **454** is oriented at approximately a Brewster's angle relative to the laser output wavelength so as to maximize the transmission of the output wavelength. In the embodiment just described, the polarization direction of the output wavelength is perpendicular to the polarization direction **421**.

Preferred embodiments may use optics **405** to separate the desired output wavelength, i.e. the laser output **450**, from the other unwanted wavelengths **451**. The optics **405** may include a beam splitter, a prism, a grating, or other optical elements. In some embodiments, the combination of walk-off and the angle of the output surface **454** of the crystal **404** may achieve sufficient separation of the laser output **450** from the other wavelengths that the optics **405** are not required.

FIG. **4**B illustrates an alternative embodiment of a frequency mixer **400**B in which type-I mixing is used for the first frequency mixing stage and type II-mixing is used for the final frequency mixing stage. The first frequency mixing stage includes a non-linear crystal **402'**, such as CLBO. The fourth harmonic (4ω) and the signal (ω_s) wavelength enter the crystal **402'** approximately collinearly along a direction **410'** and are focused to beam waists inside or proximate to the crystal **402'** (beam waists not shown). In this embodiment, both the signal wavelength and the fourth harmonic are polarized with their electric-field vectors substantially parallel to one another in the direction shown by the arrow **420'**. The plane containing the o axes of the crystal **402'** is parallel to the plane containing the directions **420'** and the direction of propagation of the light in the crystal **402'**. The e axis of the crystal **402'** is perpendicular to the plane of the page of FIG. **4**B. The o axes of the crystal **402'** are rotated at an angle relative to the direction of the light propagating in the crystal **402'** so as to achieve phase matching. For type I matching in CLBO at a temperature of approximately 100° C. with a signal wavelength near 1416 nm and a fourth harmonic wavelength near 266 nm, this angle is approximately 53.5°. For BBO at approximately 100° C. with similar wavelengths, this angle is approximately 42.4°. One skilled in the appropriate arts understands how to choose different combinations of temperature and angle to achieve phase matching.

In some embodiments, an input surface **442'** of the crystal **402'** is cut so as to be approximately at Brewster's angle relative to the direction **410'** for the fourth harmonic wavelength. This angle minimizes reflection of the fourth harmonic wavelength without needing any anti-reflection coating on the input surface **442'**. In some embodiments, the input surface **442'** may have an anti-reflection coating to reduce the reflected light at the fourth harmonic and/or the signal wavelengths. An output surface **452'** of the crystal **402'** may be coated or uncoated. The advantage of not coating is that coatings can have a short lifetime when exposed to intense UV radiation.

An output light **412'** from the crystal **402'** is directed by optics **403'** to the final frequency mixing stage including a non-linear crystal **404'**. The optics **403'** performs the same functions as the optics **403** described above in reference to FIG. **4**A. The optics **403'** may be implemented with similar elements to those described for the optics **403**. Some embodiments of the frequency mixer **400**B may omit the optics **403'**.

A direction **421'** is the direction of the electric field of both the signal and any unconsumed fourth harmonic. The direction **421'** is substantially parallel to the direction **420'** of the signal wavelength. The light at the wavelength corresponding to the sum of the signal and fourth harmonic is polarized perpendicularly to the direction **421'**.

In the frequency mixer **400**B, a crystal **404'** may have its input surface **444'** oriented at approximately Brewster's angle for the wavelength corresponding to the sum of the signal and fourth harmonic. In such embodiments, the surface **444'** can be uncoated, which has the advantage of reducing the susceptibility to damage by high intensity UV radiation. In other embodiments, the surface **444'** may have an anti-reflection coating. In some embodiments, the surface **444'** may be substantially perpendicular to the light **412**. The crystal **404'** is oriented so that the plane containing its o axes is substantially perpendicular to the direction **421'**, and its e axis is substantially parallel to the direction **421'**. The o axes of the crystal **404'** are rotated by an angle relative to direction of propagation of the light inside the crystal **404'** so as to achieve phase matching. For type-II matching in CLBO at approximately 100° C. with wavelengths of approximately 1416 nm and 224 nm, this angle is approximately 72.7°, and for BBO at approximately 100° C. for similar wavelengths, this angle is approximately 53.1°. In some embodiments, an output surface **454'** of the crystal **404'** is oriented at approximately Brewster's angle relative to the laser output wavelength so as to maximize the transmission of the output wavelength. In the frequency mixer **400**B, the polarization direction of the laser output **450'** is perpendicular to the direction **421'**.

Some preferred embodiments of the frequency mixer **400**B use optics **405'** to separate laser output **450'** from other unwanted wavelengths **451'**. The optics **405'** may include a beam splitter, a prism, a grating, or other optical elements. In some embodiments, the combination of walk-off and the angle of the output surface **454'** of crystal **404'** may achieve sufficient separation of the laser output **450'** from the unwanted wavelengths **451'** that the optics **405'** are not required.

In preferred embodiments of the frequency mixers **400**A and **400**B, a substantial fraction, or almost all, of the input fourth harmonic is consumed in the crystal **402**/**402'** due to the use of a high power at the signal wavelength. Some preferred embodiments use high enough power levels for the signal that a substantial fraction, or almost all, of the sum plus signal frequency created in the crystal **402**/**402'** is consumed in the crystal **404**/**404'**.

When CLBO crystals are used for the final two mixing stages (i.e. **402** and **404** in frequency mixer **400**A, or **402'** and **404'** in frequency mixer **400**B), the embodiment of FIG. **4**A using type II mixing followed by type I mixing has the advantage of having approximately twice as large non-linear coefficient for the final mixing (approximately 1 pm/V compared with approximately 0.5 pm/V), whereas the non-linear coefficients are similar for the first mixing stage.

When BBO crystals are used for both first and final stages, the difference in efficiency between the embodiments of FIGS. **4**A and **4**B is small because type-I conversion is about approximately two times more efficient than type-II for both mixing stages.

In some embodiments, in order to generate sufficient power at the fundamental wavelength of approximately 1064 nm, one or more amplifiers may be used to increase the power of the fundamental. If two or more amplifiers are used, then one

seed laser should preferably be used to seed all the amplifiers so that they all output the same wavelength and the laser pulses are synchronized. FIG. **5** illustrates an exemplary amplifier module **500** in which a seed laser **503** can generate stabilized, narrow-band seed laser light **504** at the desired fundamental wavelength (e.g. approximately 1064 nm). In some embodiments, the seed laser **503** is one of a Nd doped YAG laser, a Nd-doped yttrium orthovanadate laser, a fiber laser, or a stabilized diode laser. The seed light **504** goes to a first amplifier **507** that amplifies the light to a higher power level. In some embodiments, the first amplifier **507** comprises Nd-doped YAG or Nd-doped yttrium orthovanadate. In one embodiment, an amplifier pump **505** includes a laser that can pump the first amplifier **507**. In some embodiments, this pumping can be done using one or more diode lasers operating at approximately 808 nm in wavelength or at approximately 888 nm in wavelength. In other embodiments, the first amplifier **507** may comprise an Yb-doped fiber amplifier.

FIG. **5** also illustrates exemplary additional components that may be used in some embodiments of the amplifier module **500**. Because the OPO/OPA **116**, the frequency doubling module **110**, and the frequency combiner **133** (FIGS. **1**A, **1**B, **1**C) receive the fundamental laser wavelength as an input and depending on the output power required near 193.4 nm in wavelength, more fundamental laser light may be required that can be conveniently generated in a single amplifier at the required bandwidth, stability and beam quality. Indeed, increasing the power output of an optical amplifier can lead to increased bandwidth, degradation in the beam quality due to thermal lensing or other effects, reduced stability, and/or shortened lifetime.

Therefore, in some embodiments of the amplifier module **500**, the first amplifier **507** and an additional second amplifier **517** can be used to respectively generate two fundamental laser outputs **128** and **528**, which are directed to different frequency conversion stages. The second amplifier **517** can be substantially identical to the first amplifier **507**. In one embodiment, an amplifier pump **515** includes a laser that can pump the second amplifier **517**. The amplifier pump **515** can be substantially identical to the amplifier pump **505**. Notably, the same seed laser **503** can be used to seed both lasers in order to ensure that the outputs **128** and **528** are at the same wavelength and are synchronized. A beam splitter **511** and a mirror **512** can divide the seed light **504** and direct a fraction of it to the second amplifier **517**.

FIG. **6** illustrates an exemplary OPO/OPA **600** configured to generate the down-converted signal at frequency ω_s. In this embodiment, a beam combiner **611** combines an input laser light **600** at the fundamental wavelength (the wavelength corresponding to the fundamental frequency ω) and seed laser light **604** at a wavelength corresponding to the down-converted signal frequency ω_s, which is generated by a seed laser **603**.

The beam combiner **611** may comprise a dichroic coating that efficiently reflects a first wavelength while transmitting a second wavelength (for example, the beam combiner **611** may reflect the fundamental and transmit the seed laser light as shown, or vice-versa, not shown). After the beam combiner, the first and second wavelengths travel substantially collinearly through a non-linear converter **607**, which may comprise periodically poled lithium niobate, magnesium oxide doped lithium niobate, KTP, or another suitable non-linear crystalline material.

In some preferred embodiments, the seed laser **603**, such as a diode laser or a low-powered fiber laser, generates the seed laser light **604** having a wavelength of approximately 1416 nm (such as within a range from about 1330 nm to about 1612 nm, or within a range from about 1378 nm to 1461 nm, or within a range from about 1413 nm to about 1417 nm), which is then used to seed the down conversion process at the design frequency ω_s. The seed laser **603** need only be of approximately 1 mW, a few mW, or a few tens of mW in power. In some preferred embodiments, the seed laser **603** is stabilized by using, for example, a grating and stabilizing the temperature. The seed laser **603** should preferably generate polarized light, which is then introduced into the non-linear converter **607** polarized substantially perpendicular to the polarization of the fundamental, i.e. the input laser light **602**. In some embodiments, a non-linear crystal may be contained in a resonant cavity of the non-linear converter **607** to create a laser/amplifier based on spontaneous emission.

In this embodiment, a beam splitter **621** (or a prism in other embodiments) can separate the down-converted signal **129** at wavelength ω_s from an unconsumed fundamental **623**. In other embodiments (not shown), the unconsumed fundamental **623** may be recirculated back to the input of the non-linear converter **607** with a time delay to match the next incoming laser pulse of the input laser light **602**. Note that the OPO/OPA **136** (FIG. **1**C) can be implemented in a similar configuration to that shown in FIG. **6** except that the input laser light **602** is at the second harmonic (2ω), rather than the fundamental (ω).

A quasi-CW laser may be constructed using a high repetition rate laser, such as a mode-locked laser operating at approximately 50 MHz or a higher repetition rate for the fundamental laser **102**. A true CW laser may be constructed using a CW laser for the fundamental laser **102**. A CW laser may need one or more of the frequency conversion stages to be contained in resonant cavities to build up sufficient power density to get efficient frequency conversion.

In one embodiment, a fundamental wavelength near 1030 nm is used instead of a fundamental of approximately 1064 nm. Such a wavelength can be generated by a laser using a gain medium of a Yb-doped YAG crystal or a Yb-doped fiber. With a 1030 nm fundamental wavelength, an OPO signal wavelength of approximately 1552.8 nm will generate a final output wavelength near 193.368 nm. A substantially similar frequency conversion scheme to the above can be used to generate the second harmonic (near 515 nm), the fourth harmonic (near 257.5 nm), the sum of the signal (ω_s) and the fourth harmonic (near 220.9 nm), and the final output wavelength. BBO or CLBO may be used for the UV frequency conversion and mixing stages. Other non-linear crystals may also be suitable for some of the frequency conversion or mixing stages.

In yet another embodiment, a fundamental wavelength near 1047 nm or near 1053 nm is used instead of a fundamental of approximately 1064 nm. A laser operating near 1047 nm or near 1053 nm may be based on Nd:YLF (neodymium-doped yttrium lithium fluoride) for example. An appropriate signal wavelength can be chosen so as to achieve the desired laser output wavelength. For example, a signal frequency ω_s having a wavelength of approximately 1480 nm can generate a laser output of $4\omega+2\omega_s$ near 193.4 nm from a fundamental near 1047 nm. Alternatively, a signal frequency corresponding to a wavelength of approximately 1457 nm could be used with a fundamental near 1053 nm to generate a similar laser output.

In yet other embodiments, fundamental laser wavelengths near 1030 nm, 1047 nm, or 1053 nm can generate an output wavelength of approximately 193.4 nm using $3\omega+2\omega_s$, where ω_s is approximately 885 nm, 867 nm, or 861 nm, respectively.

The improved 193 nm laser is less complex and more efficient than, for example, 8th harmonic generation (which

generally needs more frequency conversion stages), and much less complex than combining two different fundamental wavelengths. Therefore, the above-described improved 193 nm laser can provide significant system advantages during photomask, reticle, or wafer inspection.

The improved 193 nm laser has several advantages compared with the laser of U.S. patent application Ser. No. 13/797,939, filed by Chuang et al. on Mar. 12, 2013 (P3913). A first advantage is that the final frequency conversion stage of the improved 193 nm laser is more efficient at generating higher output power for a given fundamental power, or a lower power fundamental for the same output power. A second advantage is that optical components and test equipment operating near 1.4 μm or 1.5 μm are more readily available than near 2.1 μm in wavelength. A third advantage is that for a signal wavelength near 1.4 μm or 1.5 μm significantly more energy goes into the signal compared with the idler, thereby resulting in more efficient conversion of fundamental power to output power (compared with a signal wavelength near 2.1 μm where almost equal amounts of power must go into the signal and the idler). A fourth advantage is that a signal wavelength near 1.4 μm or near 1.5 μm is not close to any water or —OH absorption peak, therefore leading to greater tolerance of small amounts of moisture in any of the crystals or in the light path. A sixth advantage is that the final frequency mixing stage (e.g. frequency mixing module **103**, FIG. **1**A) uses only two input wavelengths (i.e. the fourth harmonic and the signal) instead of three input wavelengths (i.e. the fourth harmonic, the fundamental, and the signal). Note that many of the same advantages apply to the improved 193 nm laser (FIG. **1**C) that combines the third harmonic with a signal wavelength between about 800 nm and 900 nm in wavelength.

Fundamental lasers operating near 1064 nm, 1053 nm, 1047 nm, and 1030 nm in wavelength are readily available at a range of different power levels and repetition rates including mode-locked, Q-switched, quasi-CW, and true CW lasers. The improved 193 nm laser is capable of operating at repetitions rates higher than 1 MHz, which is important for high-speed inspection applications. The use of mode-locked or quasi-CW fundamental laser operating at a repetition rate greater than 50 MHz, is particularly advantageous for high-speed inspection of semiconductor wafers, photomasks, and reticles because it allows high-speed image acquisition and reduces the peak power of each pulse (and so causes less damage to the optics and to the article being inspected) compared with a lower repetition rate laser of the same power. Although the above embodiments describe using various fundamental wavelengths to generate a laser output of 193.3 nm, other wavelengths within a few nanometers of 193.3 nm can be generated using an appropriate choice of signal wavelength. Such lasers and systems utilizing such lasers are within the scope of this invention.

FIGS. **7**-**14** illustrate systems that can include one of the above-described improved 193 nm lasers. These systems can be used in photomask, reticle, or wafer inspection and metrology applications.

FIG. **7** shows a reticle, photomask, or wafer inspection system **700** that simultaneously detects two channels of image or signal on one sensor **770**. The illumination source **709** incorporates an improved 193 nm laser as described herein. The light source may further comprise a pulse multiplier and/or a coherence reducing scheme. The two channels may comprise reflected and transmitted intensity when an inspected object **730** is transparent (for example a reticle or photomask), or may comprise two different illumination modes, such as angles of incidence, polarization states, wavelength ranges or some combination thereof.

As shown in FIG. **7**, illumination relay optics **715** and **720** relay the illumination from source **709** to the inspected object **730**. The inspected object **730** may be a reticle, a photomask, a semiconductor wafer or other article to be inspected. Image relay optics **740**, **755**, and **760** relay the light that is reflected and/or transmitted by the inspected object **730** to the sensor **770**. The data corresponding to the detected signals or images for the two channels is shown as data **780** and is transmitted to a computer (not shown) for processing.

Other details of an embodiment of a reticle or photomask inspection system that may be configured to measure transmitted and reflected light from the reticle or photomask are described in U.S. Pat. Nos. 7,352,457 and 7,528,943, which are incorporated by reference herein. Additional details on reticle and photomask inspection systems that may incorporate the improved 193 nm laser are provided by U.S. Pat. Nos. 7,528,943 and 5,563,702, both of which are incorporated by reference herein.

FIG. **8** illustrates an exemplary inspection system **800** including multiple objectives and one of the above-described improved 193 nm lasers. In system **800**, illumination from a laser source **801** is sent to multiple sections of the illumination subsystem. A first section of the illumination subsystem includes elements **802***a* through **806***a*. Lens **802***a* focuses light from laser source **801**. Light from lens **802***a* then reflects from mirror **803***a*. Mirror **803***a* is placed at this location for the purposes of illustration, and may be positioned elsewhere. Light from mirror **803***a* is then collected by lens **804***a*, which forms illumination pupil plane **805***a*. An aperture, filter, or other device to modify the light may be placed in pupil plane **805***a* depending on the requirements of the inspection mode. Light from pupil plane **805***a* then passes through lens **806***a* and forms illumination field plane **807**.

A second section of the illumination subsystem includes elements **802***b* through **806***b*. Lens **802***b* focuses light from laser source **801**. Light from lens **802***b* then reflects from mirror **803***b*. Light from mirror **803***b* is then collected by lens **804***b* which forms illumination pupil plane **805***b*. An aperture, filter, or other device to modify the light may be placed in pupil plane **805***b* depending on the requirements of the inspection mode. Light from pupil plane **805***b* then passes through lens **806***b* and forms illumination field plane **807**. The light from the second section is then redirected by mirror or reflective surface such that the illumination field light energy at illumination field plane **807** is comprised of the combined illumination sections.

Field plane light is then collected by lens **809** before reflecting off a beamsplitter **810**. Lenses **806***a* and **809** form an image of first illumination pupil plane **805***a* at objective pupil plane **811**. Likewise, lenses **806***b* and **809** form an image of second illumination pupil plane **805***b* at objective pupil plane **811**. An objective **812** (or alternatively **813**) then takes the pupil light and forms an image of illumination field **807** at sample **814**. Objective **812** or objective **813** can be positioned in proximity to sample **814**. Sample **814** can move on a stage (not shown), which positions the sample in the desired location. Light reflected and scattered from the sample **814** is collected by the high NA catadioptric objective **812** or objective **813**. After forming a reflected light pupil at objective pupil plane **811**, light energy passes through beamsplitter **810** and lens **815** before forming an internal field **816** in the imaging subsystem. This internal imaging field is an image of sample **814** and correspondingly illumination field **807**. This field may be spatially separated into multiple fields corresponding to the illumination fields. Each of these fields

can support a separate imaging mode. For example, one imaging mode may be a bright-field imaging mode, while another may be a dark-field imaging mode.

One of these fields can be redirected using mirror **817**. The redirected light then passes through lens **818***b* before forming another imaging pupil **819***b*. This imaging pupil is an image of pupil **811** and correspondingly illumination pupil **805***b*. An aperture, filter, or other device to modify the light may be placed in pupil plane **819***b* depending on the requirements of the inspection mode. Light from pupil plane **819***b* then passes through lens **820***b* and forms an image on sensor **821***b*. In a similar manner, light passing by mirror or reflective surface **817** is collected by lens **818***a* and forms imaging pupil **819***a*. Light from imaging pupil **819***a* is then collected by lens **820***a* before forming an image on detector **821***a*. Light imaged on detector **821***a* can be used for a different imaging mode from the light imaged on sensor **821***b*.

The illumination subsystem employed in system **800** is composed of laser source **801**, collection optics **802-804**, beam shaping components placed in proximity to a pupil plane **805**, and relay optics **806** and **809**. An internal field plane **807** is located between lenses **806** and **809**. In one preferred configuration, laser source **801** can include one of the above-described improved 193 nm lasers.

With respect to laser source **801**, while illustrated as a single uniform block having two points or angles of transmission, in reality this represents a laser source able to provide two channels of illumination, for example a first channel of light energy such as laser light energy at a first frequency (e.g. a deep UV wavelength near 193 nm) which passes through elements **802***a*-**806***a*, and a second channel of light energy such as laser light energy at a second frequency (e.g. a different harmonic, such as the 4^{th} harmonic, from the same laser, or a light from a different laser) which passes through elements **802***b*-**806***b*.

While light energy from laser source **801** is shown to be emitted 90 degrees apart, and the elements **802***a*-**806***a* and **802***b*-**806***b* are oriented at 90 degree angles, in reality light may be emitted at various orientations, not necessarily in two dimensions, and the components may be oriented differently than as shown. FIG. **8** is therefore simply a representation of the components employed and the angles or distances shown are not to scale nor specifically required for the design.

Elements placed in proximity to pupil plane **805***a*/**805***b* may be employed in the current system using the concept of aperture shaping. Using this design, uniform illumination or near uniform illumination may be realized, as well as individual point illumination, ring illumination, quadrapole illumination, or other desirable patterns.

Various implementations for the objectives may be employed in a general imaging subsystem. A single fixed objective may be used. The single objective may support all the desired imaging and inspection modes. Such a design is achievable if the imaging system supports a relatively large field size and relatively high numerical aperture. Numerical aperture can be reduced to a desired value by using internal apertures placed at the pupil planes **805***a*, **805***b*, **819***a*, and **819***b*.

Multiple objectives may also be used as shown in FIG. **8**. For example, although two objectives **812** and **813** are shown, any number is possible. Each objective in such a design may be optimized for each wavelength produced by laser source **801**. These objectives **812** and **813** can either have fixed positions or be moved into position in proximity to the sample **814**. To move multiple objectives in proximity to the sample, rotary turrets may be used as are common on standard microscopes. Other designs for moving objectives in proximity of a sample are available, including but not limited to translating the objectives laterally on a stage, and translating the objectives on an arc using a goniometer. In addition, any combination of fixed objectives and multiple objectives on a turret can be achieved in accordance with the present system.

The maximum numerical apertures of this configuration may approach or exceed 0.97, but may in certain instances be smaller. The wide range of illumination and collection angles possible with this high NA catadioptric imaging system, combined with its large field size allows the system to simultaneously support multiple inspection modes. As may be appreciated from the previous paragraphs, multiple imaging modes can be implemented using a single optical system or machine in connection with the illumination device. The high NA disclosed for illumination and collection permits the implementation of imaging modes using the same optical system, thereby allowing optimization of imaging for different types of defects or samples.

The imaging subsystem also includes intermediate image forming optics **815**. The purpose of the image forming optics **815** is to form an internal image **816** of sample **814**. At this internal image **816**, a mirror **817** can be placed to redirect light corresponding to one of the inspection modes. It is possible to redirect the light at this location because the light for the imaging modes are spatially separate. The image forming optics **818** (**818***a* and **818***b*) and **820** (**820***a* and **820***b*) can be implemented in several different forms including a varifocal zoom, multiple afocal tube lenses with focusing optics, or multiple image forming mag tubes. U.S. Published Application 2009/0180176, which published on Jul. 16, 2009 and is incorporated by reference herein, describes additional details regarding system **800**.

FIG. **9** illustrates the addition of a normal incidence laser dark-field illumination to a catadioptric imaging system **900**. The dark-field illumination includes a laser **901**, adaptation optics **902** to control the illumination beam size and profile on the surface being inspected, an aperture and window **903** in a mechanical housing **904**, and a prism **905** to redirect the laser along the optical axis at normal incidence to the surface of a sample **908**. Prism **905** also directs the specular reflection from surface features of sample **908** and reflections from the optical surfaces of an objective **906** along the optical path to an image plane **909**. Lenses for objective **906** can be provided in the general form of a catadioptric objective, a focusing lens group, and a zooming tube lens section. In a preferred embodiment, laser **901** can be implemented by the one of the above-described improved 193 nm lasers. Published US Patent Application 2007/0002465, which published on Jan. 4, 2007 and is incorporated by reference herein, describes system **900** in further detail.

FIG. **10**A illustrates a surface inspection apparatus **1000** that includes illumination system **1001** and collection system **1010** for inspecting areas of surface **1011**. As shown in FIG. **10**A, a laser system **1020** directs a light beam **1002** through a lens **1003**. In a preferred embodiment, laser system **1020** includes one of the above-described improved 193 nm lasers, an annealed crystal, and a housing to maintain the annealed condition of the crystal during standard operation by protecting it from moisture or other environmental contaminants. First beam shaping optics can be configured to receive a beam from the laser and focus the beam to an elliptical cross section at a beam waist in or proximate to the crystal.

Lens **1003** is oriented so that its principal plane is substantially parallel to a sample surface **1011** and, as a result, illumination line **1005** is formed on surface **1011** in the focal plane of lens **1003**. In addition, light beam **1002** and focused beam **1004** are directed at a non-orthogonal angle of inci-

dence to surface **1011**. In particular, light beam **1002** and focused beam **1004** may be directed at an angle between about 1 degree and about 85 degrees from a normal direction to surface **1011**. In this manner, illumination line **1005** is substantially in the plane of incidence of focused beam **1004**.

Collection system **1010** includes lens **1012** for collecting light scattered from illumination line **1005** and lens **1013** for focusing the light coming out of lens **1012** onto a device, such as charge coupled device (CCD) **1014**, comprising an array of light sensitive detectors. In one embodiment, CCD **1014** may include a linear array of detectors. In such cases, the linear array of detectors within CCD **1014** can be oriented parallel to illumination line **1015**. In one embodiment, multiple collection systems can be included, wherein each of the collection systems includes similar components, but differ in orientation.

For example, FIG. **10**B illustrates an exemplary array of collection systems **1031**, **1032**, and **1033** for a surface inspection apparatus (wherein its illumination system, e.g. similar to that of illumination system **1001**, is not shown for simplicity). First optics in collection system **1031** collect light scattered in a first direction from the surface of sample **1011**. Second optics in collection system **1032** collect light scattered in a second direction from the surface of sample **1011**. Third optics in collection system **1033** collect light scattered in a third direction from the surface of sample **1011**. Note that the first, second, and third paths are at different angles of incidence to said surface of sample **1011**. A platform **1035** supporting sample **1011** can be used to cause relative motion between the optics and sample **1011** so that the whole surface of sample **1011** can be scanned. U.S. Pat. No. 7,525,649, which issued on Apr. 28, 2009 and is incorporated by reference herein, describes surface inspection apparatus **1000** and other multiple collection systems in further detail.

FIG. **11** illustrates a surface inspection system **1100** that can be used for inspecting anomalies on a surface **1101**. In this embodiment, surface **1101** can be illuminated by a substantially stationary illumination device portion of a laser system **1130** comprising one of the above-described improved 193 nm lasers. The output of laser system **1130** can be consecutively passed through polarizing optics **1121**, a beam expander and aperture **1122**, and beam-forming optics **1123** to expand and focus the beam.

The focused laser beam **1102** is then reflected by a beam folding component **1103** and a beam deflector **1104** to direct the beam **1105** towards surface **1101** for illuminating the surface. In the preferred embodiment, beam **1105** is substantially normal or perpendicular to surface **1101**, although in other embodiments beam **1105** may be at an oblique angle to surface **1101**.

In one embodiment, beam **1105** is substantially perpendicular or normal to surface **1101** and beam deflector **1104** reflects the specular reflection of the beam from surface **1101** towards beam turning component **1103**, thereby acting as a shield to prevent the specular reflection from reaching the detectors. The direction of the specular reflection is along line SR, which is normal to the surface **1101** of the sample. In one embodiment where beam **1105** is normal to surface **1101**, this line SR coincides with the direction of illuminating beam **1105**, where this common reference line or direction is referred to herein as the axis of inspection system **1100**. Where beam **1105** is at an oblique angle to surface **1101**, the direction of specular reflection SR would not coincide with the incoming direction of beam **1105**; in such instance, the line SR indicating the direction of the surface normal is referred to as the principal axis of the collection portion of inspection system **1100**.

Light scattered by small particles are collected by mirror **1106** and directed towards aperture **1107** and detector **1108**. Light scattered by large particles are collected by lenses **1109** and directed towards aperture **1110** and detector **1111**. Note that some large particles will scatter light that is also collected and directed to detector **1107**, and similarly some small particles will scatter light that is also collected and directed to detector **1111**, but such light is of relatively low intensity compared to the intensity of scattered light the respective detector is designed to detect. In one embodiment, detector **1111** can include an array of light sensitive elements, wherein each light sensitive element of the array of light sensitive elements is configured to detect a corresponding portion of a magnified image of the illumination line. In one embodiment, inspection system can be configured for use in detecting defects on unpatterned wafers. U.S. Pat. No. 6,271,916, which issued to Marx et al. on Aug. 7, 2001 and is incorporated by reference herein, describes inspection system **1100** in further detail.

FIG. **12** illustrates an inspection system **1200** configured to implement anomaly detection using both normal and oblique illumination beams. In this configuration, a laser system **1230**, which includes one of the above-described improved 193 nm lasers, can provide a laser beam **1201**. A lens **1202** focuses the beam **1201** through a spatial filter **1203** and lens **1204** collimates the beam and conveys it to a polarizing beam splitter **1205**. Beam splitter **1205** passes a first polarized component to the normal illumination channel and a second polarized component to the oblique illumination channel, where the first and second components are orthogonal. In the normal illumination channel **1206**, the first polarized component is focused by optics **1207** and reflected by mirror **1208** towards a surface of a sample **1209**. The radiation scattered by sample **1209** is collected and focused by a paraboloidal mirror **1210** to a detector or photomultiplier tube **1211**.

In the oblique illumination channel **1212**, the second polarized component is reflected by beam splitter **1205** to a mirror **1213** which reflects such beam through a half-wave plate **1214** and focused by optics **1215** to sample **1209**. Radiation originating from the oblique illumination beam in the oblique channel **1212** and scattered by sample **1209** is collected by paraboloidal mirror **1210** and focused to photomultiplier tube **1211**. Detector or photomultiplier tube **1211** has a pinhole entrance. The pinhole and the illuminated spot (from the normal and oblique illumination channels on surface **1209**) are preferably at the foci of the paraboloidal mirror **1210**.

The paraboloidal mirror **1210** collimates the scattered radiation from sample **1209** into a collimated beam **1216**. Collimated beam **1216** is then focused by an objective **1217** and through an analyzer **1218** to the photomultiplier tube **1211**. Note that curved mirrored surfaces having shapes other than paraboloidal shapes may also be used. An instrument **1220** can provide relative motion between the beams and sample **1209** so that spots are scanned across the surface of sample **1209**. U.S. Pat. No. 6,201,601, which issued to Vaez-Iravani et al. on Mar. 13, 2001 and is incorporated by reference herein, describes inspection system **1200** in further detail.

FIG. **13** illustrates an exemplary pulse multiplier **1300** for use with the above-described improved 193 nm laser in an inspection or metrology system. Pulse multiplier **1300** is configured to generate pulse trains from each input pulse **1301** from improved 193 nm laser **1310**. Input pulse **1301** impinges on a polarizing beam splitter **1302**, which because of the polarization of input pulse **1301**, transmits all of its light to a lens **1306**. Thus, the transmitted polarization is parallel to the input polarization of input pulse **1301**. Lens

1306 focuses and directs the light of input pulse 1301 to a half-wave plate 1305. In general, a wave plate can shift the phases between perpendicular polarization components of a light wave. For example, a half-wave plate receiving linearly polarized light can generate two waves, one wave parallel to the optical axis and another wave perpendicular to the optical axis. In half-wave plate 1305, the parallel wave can propagate slightly slower than the perpendicular wave. Half-wave plate 105 is fabricated such that for light exiting, one wave is exactly half of a wavelength delayed (180 degrees) relative to the other wave.

Thus, half-wave plate 1305 can generate pulse trains from each input pulse 1301. The normalized amplitudes of the pulse trains are: cos 2θ (wherein θ is the angle of half-wave plate 1305), $\sin^2 2\theta$, $\sin^2 2\theta \cos 2\theta$, $\sin^2 2\theta \cos^2 2\theta$, $\sin^2 2\theta \cos^3 2\theta$, $\sin^2 2\theta \cos^4 2\theta$, $\sin^2 2\theta \cos^5 2\theta$, etc. Notably, the total energy of the pulse trains from a laser pulse can be substantially conserved traversing half-wave plate 1305.

The sum of the energy from the odd terms generated by half-wave plate 1305 is equal to:

$$(\cos 2\theta)^2 + (\sin^2 2\theta \cos 2\theta)^2 + (\sin^2 2\theta \cos^3 2\theta)^2 + (\sin^2 2\theta \cos^5 2\theta)^2 + (\sin^2 2\theta \cos^7 2\theta)2 + (\sin^2 2\theta \cos^9 2\theta)^2 + \ldots = \cos^2 2\theta + \sin^4 2\theta(\cos^2 2\theta + \cos^6 2\theta + \cos^{10} 2\theta + \ldots) = 2\cos^2 2\theta / (1 + \cos^2 2\theta)$$

In contrast, the sum of the energy from the even terms generated by half-wave plate 1305 is equal to:

$$(\sin^2 2\theta)^2 + (\sin^2 2\theta \cos^2 2\theta)^2 + (\sin^2 2\theta \cos^4 2\theta)^2 + (\sin^2 2\theta \cos^6 2\theta)^2 + (\sin^2 2\theta \cos^8 2\theta)^2 + (\sin^2 2\theta \cos^{10} 2\theta)^2 + \ldots = \sin^4 2\theta(1 + \cos^4 2\theta + \cos^8 2\theta + \cos^{12} 2\theta + \ldots) = \sin^2 2\theta / (1 + \cos^2 2\theta)$$

In accordance with one aspect of pulse multiplier 1300, the angle θ of half-wave plate 1305 can be determined (as shown below) to provide that the odd term sum is equal to the even term sum.

$$2\cos^2 2\theta = \sin^2 2\theta$$

$$\cos^2 2\theta = 1/3$$

$$\sin^2 2\theta = 2/3$$

$$\theta = 27.4 \text{ degrees}$$

The light exiting half-wave plate 1305 is reflected by mirrors 1304 and 1303 back to polarizing beam splitter 1302. Thus, polarizing beam splitter 1302, lens 1306, half-wave plate 1305, and mirrors 1304 and 1303 form a ring cavity configuration. The light impinging on polarizing beam splitter 1302 after traversing the ring cavity has two polarizations as generated by half-wave plate 1305. Therefore, polarizing beam splitter 1302 transmits some light and reflects other light, as indicated by arrows 1309. Specifically, polarizing beam splitter 1302 transmits the light from mirror 1303 having the same polarization as input pulse 1301. This transmitted light exits pulse multiplier 1300 as output pulses 1307. The reflected light, which has a polarization perpendicular to that of input pulse 1301, is re-introduced into the ring cavity (pulses not shown for simplicity).

Notably, these re-introduced pulses can traverse the ring in the manner described above with further partial polarization switching by half-wave plate 1305 and then light splitting by polarizing beam splitter 1302. Thus, in general, the above-described ring cavity is configured to allow some light to exit and the rest of the light (with some minimal losses) to continue around the ring. During each traversal of the ring (and without the introduction of additional input pulses), the energy of the total light decreases due to the light exiting the ring as output pulses 1307.

Periodically, a new input pulse 1301 is provided by laser 1310 to pulse multiplier 1300. In one embodiment, the laser may generate approximately 0.1 nanosecond (ns) laser pulses at a repetition rate of approximately 125 MHz, and the cavity may double the repetition rate. Note that the size of the ring, and thus the time delay of the ring, can be adjusted by moving mirror 1304 along the axis indicated by arrows 1308.

The ring cavity length may be slightly greater than, or slightly less than, the nominal length calculated directly from the pulse interval divided by the multiplication factor. This results in the pulses not arriving at exactly the same time as the polarized beam splitter and slightly broadens the output pulse. For example, when the input pulse repetition rate is 125 MHz, the cavity delay would nominally be 4 ns for a frequency multiplication by 2. In one embodiment, a cavity length corresponding to 4.05 ns can be used so that the multiply reflected pulses do not arrive at exactly the same time as an incoming pulse. Moreover, the 4.05 ns cavity length for the 125 MHz input pulse repetition rate can also advantageously broaden the pulse and reduce pulse height. Other pulse multipliers having different input pulse rates can have different cavity delays.

Notably, polarizing beam splitter 1302 and half-wave plate 1305 working in combination generate even and odd pulses, which diminish for each round traversed inside the ring. These even and odd pulses can be characterized as providing energy envelopes, wherein an energy envelope consists of an even pulse train (i.e. a plurality of even pulses) or an odd pulse train (i.e. a plurality of odd pulses). In accordance with one aspect of pulse multiplier 1300, these energy envelopes are substantially equal.

More details of pulse multiplication can be found in co-pending U.S. patent application Ser. No. 13/487,075, entitled "Semiconductor Inspection And Metrology System Using Laser Pulse Multiplier" and filed on Jun. 1, 2012, which is incorporated by reference herein. Note that the above pulse multiplier is just one example that may be used with the improved 193 nm laser. Combining this improved laser with other pulse multipliers is within the scope of this invention. For example, the improved 193 nm laser described herein may also be used with any of the laser pulse multipliers described in U.S. patent application Ser. No. 13/711,593, entitled "Semiconductor Inspection and Metrology System Using Laser Pulse Multiplier", filed by Chuang et al. on Dec. 11, 2012, and incorporated by reference herein.

FIG. 14 illustrates aspects of a pulse-shaping or coherence reducing device used in conjunction with a pulsed laser, suitable for incorporation into an inspection or metrology system in accordance with embodiments of the present invention. A light source 1410 comprises an improved 193 nm laser as described herein. The light source 1410 generates a light beam 1412 comprising a series of pulses. One aspect of this embodiment is to make use of the finite spectral range of the laser in order to perform a substantially quick temporal modulation of a light beam 1412, which can be changed on the required tenth picosecond time intervals (a tenth picoseconds time interval is equivalent to a few nm in spectral width), and transform the temporal modulation to spatial modulation.

The use of a dispersive element and an electro-optic modulator is provided for speckle reduction and/or pulse shaping.

For example, the illumination subsystem includes a dispersive element positioned in the path of the coherent pulses of light. As shown in FIG. **14**, the dispersive element can be positioned at a plane **1414** arranged at angle θ_1 to the cross-section of the coherent pulses of light. As shown in FIG. **14**, the pulses of light exit the dispersive element at angle θ_1' and with cross-sectional dimension x_1'. In one embodiment, the dispersive element is a prism. In another embodiment, the dispersive element is a diffraction grating. The dispersive element is configured to reduce coherence of the pulses of light by mixing spatial and temporal characteristics of light distribution in the pulses of light. In particular, a dispersive element such as a prism or diffraction grating provides some mixing between spatial and temporal characteristics of the light distribution in the pulses of light. The dispersive element may include any suitable prism or diffraction grating, which may vary depending on the optical characteristics of the illumination subsystem and the metrology or inspection system.

The illumination subsystem further includes an electro-optic modulator positioned in the path of the pulses of light exiting the dispersive element. For example, as shown in FIG. **14**, the illumination subsystem may include an electro-optic modulator **1416** positioned in the path of the pulses of light exiting the dispersive element. The electro-optic modulator **1416** is configured to reduce the coherence of the pulses of light by temporally modulating the light distribution in the pulses of light. In particular, the electro-optic modulator **1416** provides an arbitrary temporal modulation of the light distribution. Therefore, the dispersive element and the electro-optic modulator **1416** have a combined effect on the pulses of light generated by the light source. In particular, the combination of the dispersive element with the electro-optic modulator **1416** creates an arbitrary temporal modulation and transforms the temporal modulation to an arbitrary spatial modulation of the output beam **1418**.

In one embodiment, the electro-optic modulator **1416** is configured to change the temporal modulation of the light distribution in the pulses of light at tenth picosecond time intervals. In another embodiment, the electro-optic modulator **1416** is configured to provide about 10^3 aperiodic samples on each period thereby providing a de-coherence time of about 10^{-13} seconds.

Further details of the pulse-shaping, coherence, and speckle reducing apparatus and methods are disclosed in co-pending U.S. Published Patent Application 2011/0279819, published on Nov. 17, 2011, and U.S. Published Patent Application 2011/0228263, published on Sep. 22, 2011. Both of these applications are incorporated by reference herein.

The various embodiments of the structures and methods described herein are illustrative only of the principles of the invention and are not intended to limit the scope of the invention to the particular embodiments described. For example, non-linear crystals other than CLBO, LBO, or BBO or periodically-poled materials can be used for some of the frequency conversion and mixing stages.

The invention claimed is:

1. A laser for generating an output wavelength of approximately 193.4 nm, the laser comprising:

a fundamental laser;

a first frequency doubling module, coupled to the fundamental laser, for generating a second harmonic;

a second frequency doubling module, coupled to the first frequency doubling module, for generating a fourth harmonic;

an optical parametric generator, coupled to one of the first frequency doubling module and the fundamental laser, for generating a down-converted signal; and

a frequency mixing module, coupled to the optical parametric generator and the second frequency doubling module, for generating a laser output of a frequency equal to a sum of the fourth harmonic and twice a frequency of the down-converted signal,

wherein the frequency mixing module comprises two non-linear crystals, a first non-linear crystal configured to generate a frequency equal to a sum of the fourth harmonic and a frequency of the down-converted signal by type-I conversion, and a second non-linear crystal configured to generate the frequency equal to the sum of the fourth harmonic and the twice the frequency of the down-converted signal by type-II conversion, and

wherein the fundamental laser generates a fundamental frequency of approximately 1064.3 nm, approximately 1053 nm, approximately 1047 nm, or approximately 1030 nm.

2. The laser of claim **1**, wherein the optical parametric generator includes a periodically poled non-linear optical crystal.

3. The laser of claim **2**, wherein the periodically poled non-linear optical crystal is one of lithium niobate, magnesium-oxide doped lithium niobate, stoichiometric lithium tantalate, magnesium-oxide doped stoichiometric lithium tantalate, and potassium titanyl phosphate (KTP).

4. The laser of claim **1**, wherein the down-converted signal has a signal wavelength of approximately 1380 nm to 1612 nm.

5. The laser of claim **4**, wherein the down-converted signal has a signal wavelength of approximately 1416 nm.

6. The laser of claim **1**, wherein the laser is one of a continuous-wave laser, a Q-switched laser, a mode-locked laser, or a quasi-continuous-wave laser.

7. The laser of claim **1**, wherein the optical parametric generator includes an optical parametric amplifier or an optical parametric oscillator.

8. The laser of claim **1**, wherein the fundamental laser includes a laser diode or a fiber laser.

9. The laser of claim **1**, wherein the fundamental laser includes a cesium lithium borate (CLBO) crystal.

10. The laser of claim **1**, wherein the frequency mixing module includes a cesium lithium borate (CLBO) crystal, a beta barium borate (BBO) crystal, or a lithium triborate (LBO) crystal.

11. The laser of claim **1**, wherein the frequency mixing module comprises a hydrogen-annealed non-linear crystal.

12. An inspection system comprising:

a laser for generating an output wavelength of approximately 193.4 nm, the laser comprising:

a fundamental laser;

an optical parametric generator, coupled to the fundamental laser, for generating a down-converted signal;

a fourth harmonic generator, coupled to the optical parametric generator or to the fundamental laser, for generating a fourth harmonic; and

a frequency mixing module, coupled to the optical parametric generator and the fourth harmonic generator, for generating a laser output at a frequency equal to a sum of the fourth harmonic and twice a frequency of the down-converted signal,

wherein the frequency mixing module comprises two non-linear crystals configured so that one non-linear crystal

performs type-I frequency summation and another nonlinear crystal performs type-II frequency summation, and

wherein the inspection system further comprises a detector and optics configured to simultaneously collect reflection and transmission images using the detector.

13. The inspection system of claim **12**, wherein the inspection system is a dark-field inspection system.

14. The inspection system of claim **12**, further comprising at least one acousto-optic modulator or electro-optic modulator to reduce coherence of illumination.

15. The inspection system of claim **12**, further comprising a pulse rate multiplier to increase a pulse repetition rate.

16. The inspection system of claim **12**, further comprising components for simultaneously collecting reflection and transmission images using same detectors.

17. The inspection system of claim **12**, further comprising components for forming an illuminated line on a target being inspected.

18. The inspection system of claim **12**, further comprising components for forming multiple, simultaneously-illuminated spots on a target.

19. The inspection system of claim **12**, wherein the fundamental laser generates a fundamental frequency of approximately 1064.3 nm, approximately 1053 nm, approximately 1047 nm, or approximately 1030 nm.

20. A laser for generating an output wavelength of approximately 193.4 nm, the laser comprising:

a fundamental laser;

a frequency doubling module, coupled to the fundamental laser, for generating a second harmonic;

a frequency combiner, coupled to the frequency doubling module, for generating a third harmonic;

an optical parametric generator, coupled to one of the frequency doubling module and the frequency combiner, for generating a down-converted signal; and

a frequency mixing module, coupled to the optical parametric generator and the frequency combiner, for generating a laser output of a frequency equal to a sum of the third harmonic and twice a frequency of the down-converted signal,

wherein the fundamental laser generates a fundamental frequency of approximately 1064.3 nm, approximately 1053 nm, approximately 1047 nm, or approximately 1030 nm.

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